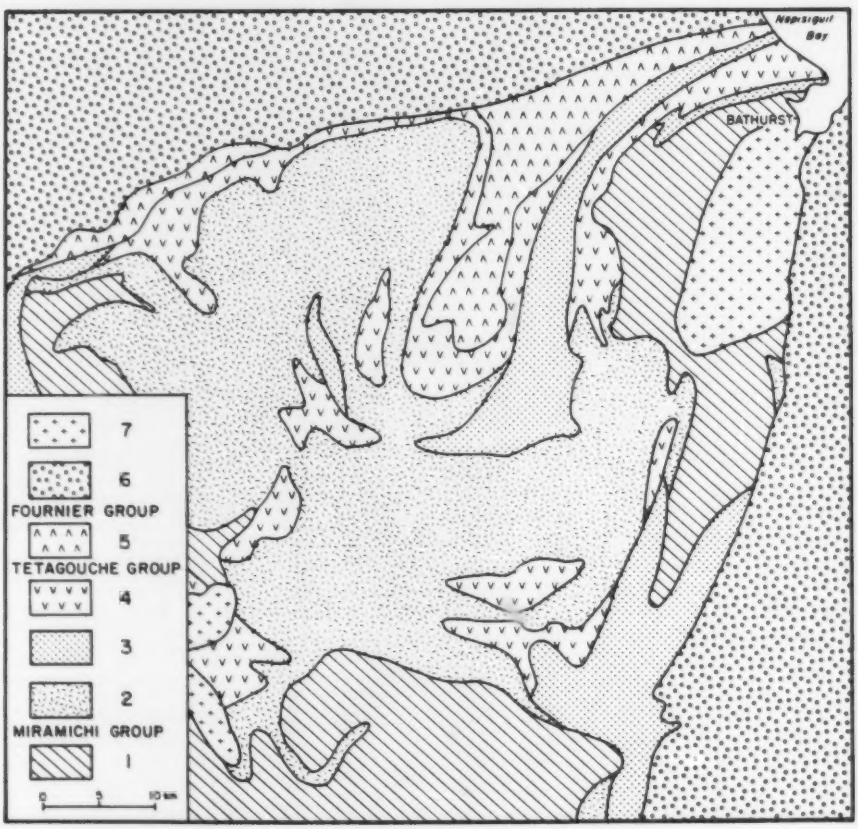
New Nouveau
Brunswick

Natural Resources and Energy
Mineral Resources

Geoscience Report 91-2

Dunnage and Gander Zones, New Brunswick: Canadian Appalachian Region

C.R. van Staal and L.R. Fyffe



ISSN 0838-2565

Price $ 5.00

Geoscience Report 91-2

Dunnage and Gander Zones, New Brunswick:

Canadian Appalachian Region

Cover:
Geology of the northern Miramichi Highlands. Map units: 1 = Cambro-Ordovician quartz wacke and slate; 2 = Ordovician porphyritic and aphyric felsic flows, pyroclastic and epiclastic rocks; 3 = Ordovician feldspathic wacke and varicoloured slates; 4 = Ordovician tholeiitic and alkalic basalts; 5 = Ordovician tholeiitic basalts, lithic wacke, limestone and slate – includes some alkali basalts in the west; 6 = Siluro-Devonian volcanic and sedimentary rocks in the north, Carboniferous sedimentary rocks in the east; 7 = Devonian granite.

This report has been prepared by:

Mineral Resources
Department of Natural Resources and Energy
Province of New Brunswick

Hon. Morris Green
Minister of Natural Resources and Energy

Hon. Edmond P. Blanchard
Minister of State for Mines

June, 1991

New Nouveau
Brunswick

91-06861/

Natural Resources and Energy
Mineral Resources

Geoscience Report 91-2

Dunnage and Gander Zones, New Brunswick: Canadian Appalachian Region

C.R. van Staal and L.R. Fyffe

ISSN 0838-2565

This report should be referenced in the following manner:

VAN STAAL, C.R., and FYFFE, L.R. 1991. Dunnage and Gander Zones, New Brunswick: Canadian Appalachian Region. New Brunswick Department of Natural Resources and Energy, Mineral Resources, Geoscience Report 91-2, 39 p.

This report is a preprint of:

VAN STAAL, C., and FYFFE, L.R. 1991. Dunnage and Gander zones, New Brunswick: Canadian Appalachian Region. *In* Chapter 3 of Geology of the Appalachian/ Caledonian Orogen in Canada and Greenland, Harold Williams (co-ord.); Geological Survey of Canada, Geology of Canada, No. 6 (also Geological Society of America, The Geology of North America, v. F-1).

TABLE OF CONTENTS

DUNNAGE ZONE 1
INTRODUCTION 1
BELLEDUNE SUBZONE 4
ELMTREE SUBZONE 7
POPELOGAN SUBZONE 9
ARMSTRONG BROOK SUBZONE 9
BATHURST SUBZONE 11
HAYESVILLE SUBZONE 17

GANDER ZONE 19
INTRODUCTION 19
MIRAMICHI SUBZONE 21
ST. CROIX SUBZONE 24

STRUCTURE AND METAMORPHISM 24

TECTONIC INTERPRETATIONS 30

SUMMARY OF GANDER-DUNNAGE RELATIONSHIPS 32

REFERENCES 32

FIGURE 1. Distribution of the pre-Silurian tectonostratigraphic subzones in New Brunswick 2
2. Geology of the Belledune and Elmtree subzones 3
3. Layered and foliated gabbroic rocks of the Devereaux Formation transected by a plagiogranite dyke, Belledune Subzone 5
4. Massive diabase transecting layering within the gabbroic rocks of the Devereaux Formation, Belledune Subzone 5
5. High-strain amphibolite zone within gabbroic rocks of the Devereaux Formation, Belledune Subzone 6
6. Sheeted dykes within the Devereaux Formation, Belledune Subzone 6
7. Upright, shallowly east-plunging F_2 folds in lithic wacke beds of the Prairie Brook Member, Pointe-Verte Formation, Belledune Subzone 7
8. Tectonostratigraphy for the Dunnage Subzone of New Brunswick 8
9. Geology of part of the Armstrong Brook and Bathurst subzones in the northern Miramichi Highlands. 10
10. Quartz and feldspar-phyric intrusion or flow in the Nepisiguit Falls Formation at Devils Elbow, Tetagouche Group, Bathurst Subzone 12
11. Upright, shallowly plunging F_2 fold in banded oxide-jasper iron formation at the top of the Nepisiguit Falls Formation, Tetagouche Group, Bathurst Subzone 12
12. Cross-bedded, sandy limestone of Vallée Lourdes Formation, Tetagouche Group, Bathurst Subzone 14
13. Thin-bedded calcareous siltstone of the Vallée Lourdes Formation, Tetagouche Group, Bathurst Subzone 14
14. Boulders of granitic gneiss in tuffaceous limestone of the Vallée Lourdes Formation, Bathurst Subzone 15

FIGURE 15. Angular felsic clasts in feldspathic wacke of the Patrick Brook Formation, Tetagouche Group at Tetagouche Falls, Bathurst Subzone 15
16. Northeast-trending F_5 crenulations refolding isoclinal F_2 folds within tuffaceous phyllite of the Patrick Brook Formation, Tetagouche Group, Bathurst Subzone 16
17. Quartz wacke pebbles in sandy limestone at the base of Vallée Lourdes Formation, Tetagouche Group, Bathurst Subzone 16
18. Schematic model of the tectonic evolution of the northern Appalachians in New Brunswick and adjacent Quebec 18
19. North-younging pillows in Beresford alkalic basalt of the Boucher Brook Formation, Tetagouche Group, Bathurst Subzone 20
20. Tightly folded, fossiliferous, calcareous siltstone of the Lower Birch Island Formation, Tetagouche Group, Hayesville Subzone 20
21. Lithic wacke of Push and Be Damned Formation containing rip-up clasts of dark grey siltstone, Hayesville Subzone 22
22. Interference pattern between upright F_2 fold and northeast-trending open F_5 fold within phyllites of the Knights Brook Formation, Miramichi Subzone 22
23. Steeply plunging F_2 fold in medium-bedded quartz wacke of the Chain of Rocks Formation, Tetagouche Group, on Middle River, Miramichi Subzone 23
24. Sole marks in quartz wackes of the Miramichi Subzone 23
25. Pillow basalt in Calais Formation of the Cookson Group, St. Croix Subzone 25
26. Isoclinal F_1 refolded by upright F_2 in interbedded wacke and slate of the Woodland Formation, Cookson Group, St. Croix Subzone 25
27. Downward-facing, southward-verging F_3 folds in interbedded wacke and slate of the Digdeguash Formation, Cookson Group, St. Croix Subzone 26
28. Tight F_1 folds in thin-bedded quartz arenite and slate of the Kendall Mountain Formation, Cookson Group, St. Croix Subzone 27
29. Foliated gabbroic boulder within Upper Silurian conglomerate of the Chaleurs Group 28
30. Recumbent F_2 folds transposed into shallow-dipping orientation by F_3 within Nepisiguit Falls Formation at Devils Elbow, Bathurst Subzone 28

DUNNAGE AND GANDER ZONES, NEW BRUNSWICK: CANADIAN APPALACHIAN REGION

DUNNAGE ZONE

INTRODUCTION

The Dunnage Zone of New Brunswick is defined on its marine Early and Middle Ordovician volcanic rocks. Locally, in the Elmtree River-Belledune River area of the Chaleur Uplands (Figure 1), volcanic rocks overlie, or are part of, an ophiolitic substrate. Throughout most of the Miramichi Highlands, volcanic rocks overlie a thick terrigenous clastic sequence with at least local preservation of stratigraphic contacts. According to this definition of the New Brunswick Dunnage Zone, its rocks overlie both an ophiolitic and continental substrate and possibly link these contrasting basement elements from north to south across the Province. Previous placement of a Dunnage-Gander boundary at the Rocky Brook-Millstream Fault (Williams 1978, 1979; Fyffe and Fricker 1987) was an attempt to separate ophiolite-based sequences to the north from clastic-based sequences to the south, rather than depict the distribution of Early and Middle Ordovician volcanic rocks. However, detailed mapping (van Staal *et al.* 1990) and extensive geochemical studies (van Staal *et al.* 1991) have shown that identical volcanic and sedimentary suites, as well as local ophiolitic rocks, occur on opposite sides of the Rocky Brook-Millstream Fault. Therefore, the fault is not an important zone or terrane boundary.

Six subzones are recognized in the New Brunswick Dunnage Zone. The Elmtree, Belledune, and Popelogan subzones occur in two discrete Ordovician inliers that are surrounded by middle Paleozoic rocks of the Chaleur Uplands to the north of the Rocky Brook-Millstream Fault (Figure 1). The inlier of Ordovician rocks in the Elmtree River-Belledune River area contains three major thrust sheets (Figure 2). From bottom to top, rocks of successively higher sheets are the Elmtree Formation, the Pointe-Verte Formation, and the ophiolitic Devereaux Formation. The Pointe-Verte and Devereaux formations define the Belledune Subzone. The Elmtree Formation defines the Elmtree Subzone. Ordovician sedimentary and volcanic rocks of the Balmoral Group, exposed in a separate inlier to the west, define the Popelogan Subzone.

Detailed mapping at 1:10 000 scale (van Staal, unpublished results) south of the Rocky Brook-Millstream Fault led to three new subzones for the Middle Ordovician volcanic and sedimentary rocks in the Miramichi Highlands (Figure 1). These are: the Armstrong Brook Subzone, which is thought to contain correlatives of the upper thrust sheets in the Belledune Subzone; the Bathurst Subzone, which has lithological similarities to the Elmtree Subzone; and the Hayesville Subzone of the southwestern Miramichi Highlands. The Armstrong Brook and Bathurst subzones are separated by a major tectonic boundary that coincides with a 70 km long belt of blueschists that are traceable across most of the northern Miramichi Highlands. The important differences between the Armstrong Brook and Bathurst subzones, which justifies their separation, are as follows: (1) north of the tectonic boundary, basalts are compositionally like those found at mid-ocean ridges (MOR) or are intermediate between MOR and island-arc tholeiites (van Staal *et al.* 1991); (2) no silicic volcanic rocks are interlayered with the basalts of the Armstrong Brook Subzone; (3) the sedimentary rocks overlying the basalts in the Armstrong Brook Subzone contain numerous limestone lenses and coarse, thick-bedded quartz- and feldspar-rich lithic wackes as in the Pointe-Verte Formation, which are rare or absent in the Bathurst Subzone; and (4) red phyllite, chert, jasper, and Zn-Pb-Cu-Ag type massive sulphides, typical of metalliferous sediments found in the Bathurst Subzone, are absent in the Armstrong Brook Subzone, which contains only one Cyprus-type, Cu-pyrite sulphide prospect, *i.e.*, Middle River Copper (Davies 1979). A syngenetic massive sulphide body in the Belledune Subzone, the Turgeon deposit (Davies *et al.* 1983), is also a Cyprus-type, Cu-pyrite body.

All of the Ordovician and older rocks of the Miramichi Highlands were assigned traditionally to the Tetagouche Group (Young 1911; Alcock 1941; Skinner and McAlary 1952). Those of the present Armstrong Brook, Bathurst, and Hayesville subzones, dominated by volcanic and volcaniclastic sedimentary rocks, were referred to informally as the upper Tetagouche Group (Ruitenberg *et al.* 1977). The underlying nonvolcanogenic quartzose clastic rocks were referred to as the lower Tetagouche Group. Since the entire Tetagouche Group has never been clearly defined, and since it contains distinct lithologies now assigned to the Dunnage and Gander zones, new names or redefinitions of existing names are required to distinguish its

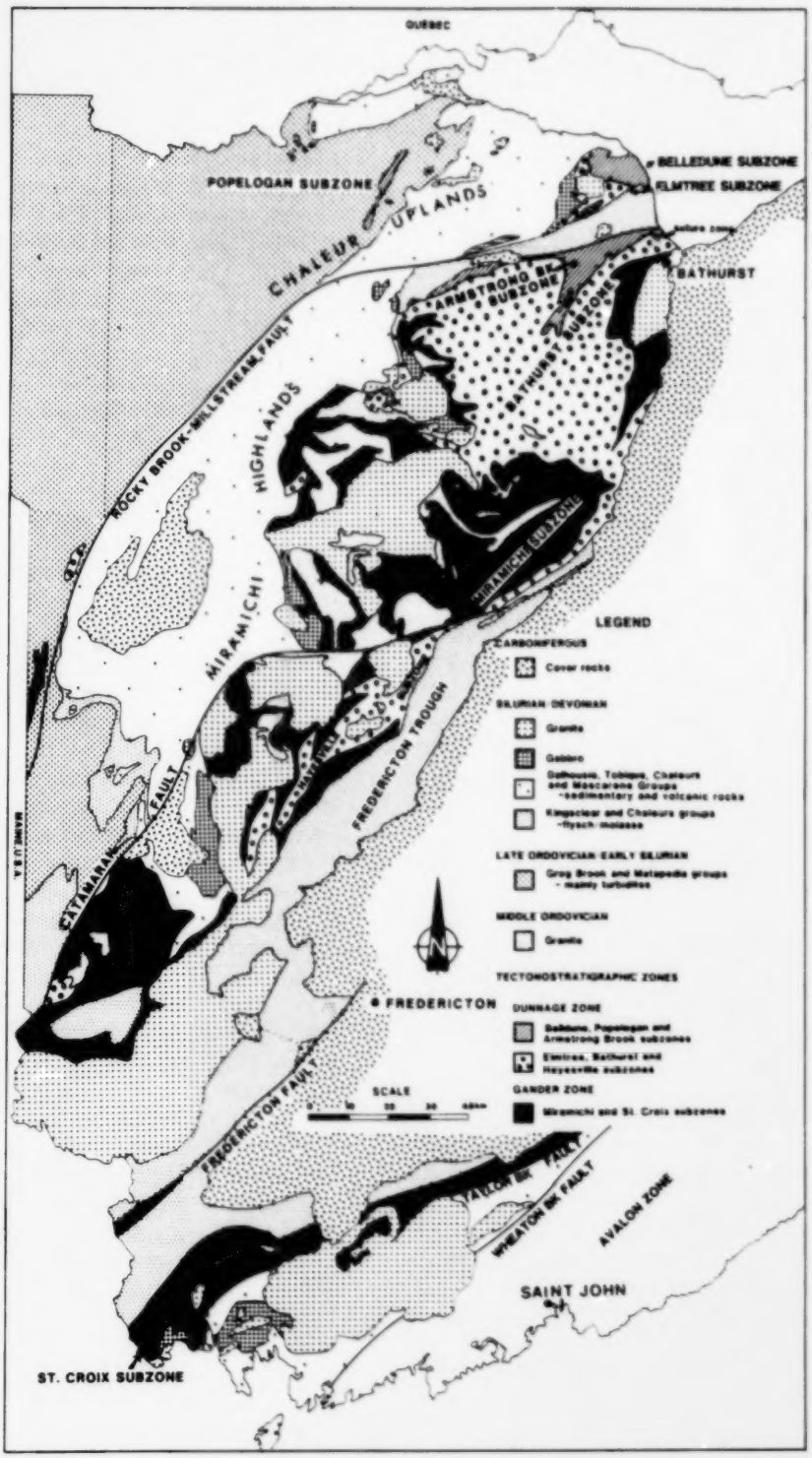


FIGURE 1. Distribution of the pre-Silurian tectonostratigraphic subzones in New Brunswick. Only the major faults are shown.

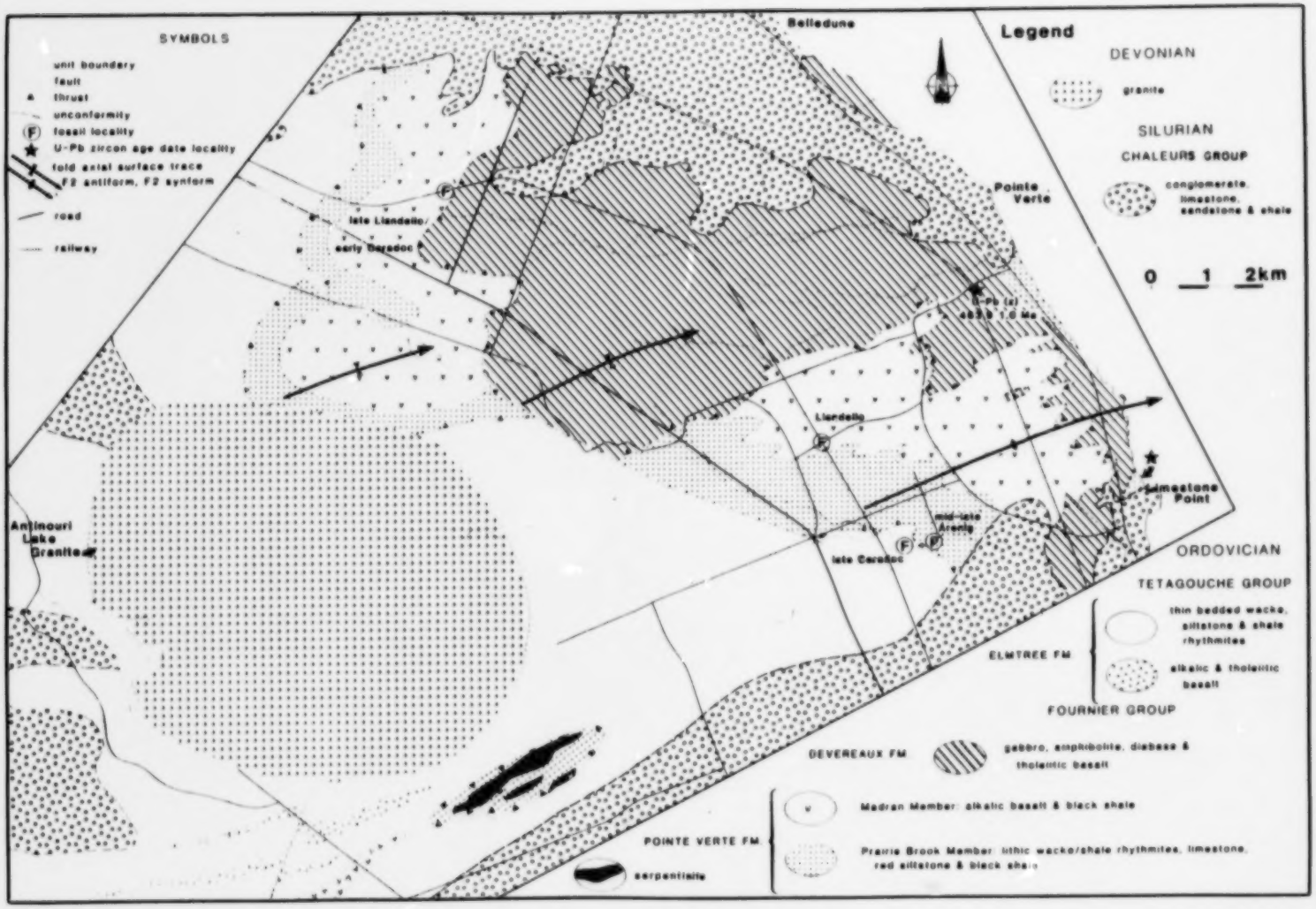


FIGURE 2. Geology of the Belledune and Elmtree subzones (modified from van Staal and Langton 1990).

Dunnage volcanosedimentary part from underlying monotonous clastic rocks assigned to the Gander Zone. We retain the name Tetagouche Group for the volcanic and associated sedimentary rocks now assigned to the Dunnage Zone in the Bathurst and Hayesville subzones of the Miramichi Highlands. A new name, Miramichi Group (*cf.*, Potter 1969), designates the underlying clastic rocks assigned to the Gander Zone.

A few minor isolated bodies of Middle Ordovician rocks occur in west-central New Brunswick (Fyffe 1982a). Small inliers of Middle Ordovician volcanic and sedimentary rocks also occur in the southern Gaspé area of Québec, *e.g.*, the Arsenault Formation (Malo 1988; Riva and Malo 1988). A much larger occurrence forms the Munsungun-Winterville Anticlinorium in the state of Maine (Hall 1970; Roy and Mencher 1976; Osberg *et al.* 1985). These inliers suggest that Middle Ordovician volcanic and sedimentary rocks probably form a continuous basement to the Late Ordovician-Devonian volcanic and sedimentary cover throughout this part of the northern Appalachians.

BELLEDUNE SUBZONE

Ordovician rocks of the Belledune Subzone (Figure 2) were named the Fournier Group (Young 1911). It was subdivided into: the Devereaux Formation, consisting of gabbro, mylonitic amphibolite, plagiogranite, and diabase, which locally defines a sheeted complex (Figures 3, 4, 5, 6); and the Pointe-Verte Formation, consisting of basalt, greywacke, shale, limestone, and chert (Pajari *et al.* 1977; Rast and Stringer 1980). The combined Devereaux and Pointe-Verte formations were interpreted as upper parts of an ophiolitic suite (Pajari *et al.* 1977). However, geochemical analyses (Winchester and van Staal 1988) show that most basalts in the Pointe-Verte Formation are alkalic, atypical of ophiolitic suites, in contrast to the tholeiitic basalts that overlie the gabbro. Furthermore, detailed mapping at 1:10 000 scale indicates that the alkalic basalts structurally underlie the Devereaux Formation; since the east-trending upright F_2 structures that fold the Ordovician rocks into a synform and antiform pair (Figures 2, 7) have shallow to moderate eastward plunges (Langton and van Staal 1989; Thomas et al. 1991). A major high-strain zone, defined by low-grade mylonites and phyllonites separates the contrasting alkalic and tholeiitic igneous suites. The Pointe-Verte Formation is, therefore, redefined to include only the alkalic basalts and associated sedimentary rocks, while the Devereaux Formation is expanded to include the tholeiitic basalts and sedimentary rocks that structurally and stratigraphically overlie its gabbroic rocks. The gabbroic rocks and tholeiitic basalts of the Devereaux Formation are interpreted as a fragment of back-arc oceanic crust (van Staal *et al.* 1991). Zircons from a coarse gabbro of the Devereaux Formation are dated at 463.9 ±1 Ma (van Staal *et al.* 1988a; Sullivan *et al.* 1990), which falls in the Llandeilian of most time scales (Harland *et al.* 1982; Palmer 1983; Snelling 1985; Haq and van Eysinga 1987). Recent calibration of the Ordovician time-scale (Tucker *et al.* 1990) suggests that this age is nearly coincident with the Llanvirnian/Llandeilian boundary (Figure 8). Sheared amphibolitized gabbro (Figure 5) is locally cut by plagiogranite dykes (Figure 3), which are themselves weakly deformed by the shear zones. One of these syntectonic plagiogranite dykes in the quarry near the Green Point railway station yielded a U-Pb zircon age of 459.6 ±1 Ma (Sullivan *et al.* 1990), whereas an age of 461 ±3 Ma was obtained by Spray *et al.* (1990) for the same dyke. An Ar^{39}/Ar^{40} hornblende cooling age of 459 ± 5 Ma for the amphibolite in the shear zone cut by the plagiogranite (C. Ravenhurst, personal communication, 1989) supports the field interpretation that the intrusion is syntectonic with respect to the shearing, and indicates an approximate age difference of 4 Ma between the gabbro and the plagiogranite. This late Llandeilian/early Caradocian age defines a phase of intraoceanic deformation, since amphibolite facies metamorphic conditions and deformation are restricted to the sheared parts of the gabbro. The age difference between the crystallization of the gabbro and the plagiogranite suggest that the plagiogranite is an off-axis intrusion, either emplaced along a transform fault (van Staal *et al.* 1990) or in an embryonic volcanic arc developed on back-arc oceanic crust (Flagler and Spray 1991). The Devereaux ophiolitic suite is thus significantly younger than the Lower Ordovician ophiolites of the Newfoundland Dunnage Zone (Dunning and Krogh 1985).

The Pointe-Verte Formation is subdivided into two members (Figure 8; Langton and van Staal 1989): a lower Prairie Brook Member, which mainly consists of thick-bedded, quartz- and feldspar-rich lithic wacke (Figure 7) with minor limestone, shale, felsic volcanic tuff, pebble conglomerate, and red siltstone; and an upper Madran Member, mainly consisting of alkalic basalts and minor interbedded rocks like those of the underlying Prairie Brook Member. Black shale occurs near the top of the Madran Member. All shales and siltstones are generally transformed into slates and phyllites. The conodont alteration index (CAI) in interbedded metalimestone ranges from 4 to 6 (Nowlan

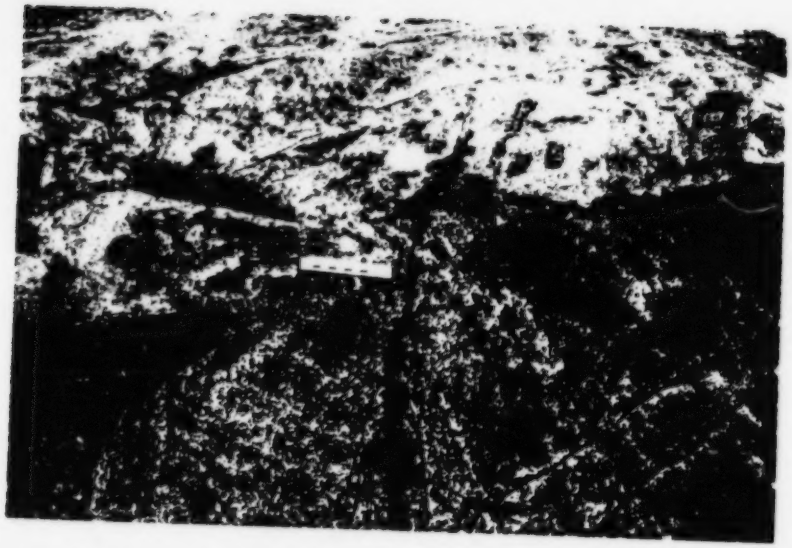


FIGURE 3. Layered and foliated gabbroic rocks of the Devereaux Formation transected by a plagiogranite dyke (light grey in upper part of photo), Belledune Subzone.

FIGURE 4. Massive diabase transecting layering within the gabbroic rocks of the Devereaux Formation, Belledune Subzone.

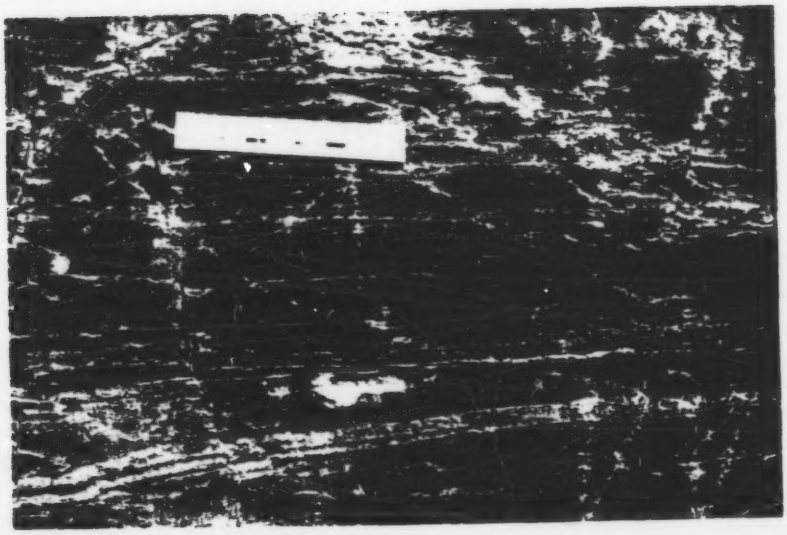


FIGURE 5. High-strain amphibolite zone within gabbroic rocks of the Devereaux Formation, Belledune Subzone.

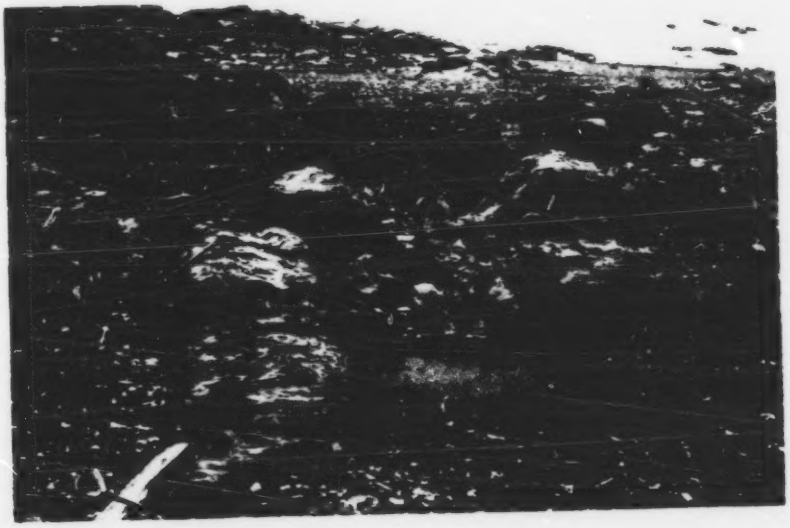


FIGURE 6. Sheeted dykes within the Devereaux Formation, Belledune Subzone.

FIGURE 7. Upright, shallowly east-plunging F_2 folds in lithic wacke beds of the Prairie Brook Member, Pointe-Verte Formation, Belledune Subzone.

1986, 1988a), indicating metamorphic temperatures from 300 to 400° C. Thin limestone layers interbedded with the lithic wacke and slate near the structural base of the Prairie Brook Member contain middle to late Arenigian conodonts (Nowlan 1988a). Interpillow limestone near the base of the Madran Member has Llandeilian conodonts (*P. anserinus* zone; Nowlan 1983, 1986), whereas black shale near the top of the Madran Member has Llandeilian to early Caradocian graptolites of the *N. gracilis* zone (Riva, in Fyffe 1986). The Pointe-Verte Formation thus spans virtually the whole Middle Ordovician and the Madran Member is partly equivalent, or more likely younger, than the Devereaux ophiolitic suite according to the time scale calibration of Tucker *et al.* (1990). The presence of diabase dykes in the gabbro complex of the Devereaux Formation, with compositions identical to the alkalic basalts in the Pointe-Verte Formation, also indicates that the Pointe Verte Formation is partly younger. The narrow zone of mylonite and phyllonite that separates the Pointe-Verte and Devereaux formations is therefore interpreted as a thrust, with the Devereaux ophiolitic suite structurally above the slightly younger rocks of the Pointe-Verte Formation.

An isolated occurrence of typical Pointe-Verte rocks with lenses of serpentinite, surrounded by mélange, occurs in the most southwestern corner of the Elmtree Inlier (Figure 2). It is tentatively interpreted as a klippe of Fournier Group rocks. Middle Ordovician rocks of the Belledune Subzone thus consist of two major thrust sheets emplaced upon the Elmtree Subzone during post-Caradocian thrusting.

ELMTREE SUBZONE

The Elmtree Formation (Young 1911) of the Elmtree Subzone structurally underlies the Pointe-Verte Formation (Figure 2). It consists of dark grey to black shale interlayered with thin-bedded siltstones and wackes, alkalic and tholeiitic basalt and minor felsic volcanic rocks with interbeds of red and green phyllite and chert. The sedimentary and volcanic rocks of the Elmtree Formation are compositionally similar to rocks in the Tetagouche Group (van Staal and Langton 1988; Winchester and van Staal, unpublished results) of the Bathurst Subzone. They are regarded, therefore, as correlatives of the Bathurst Subzone and included within the Tetagouche Group. The age of the Elmtree Formation is not well constrained by fossils, but one *Orthoqraptus* sp., indicative of a Caradocian to Llandoverian age (Dean 1975), was found in black shales along the Elmtree River, approximately 200 m

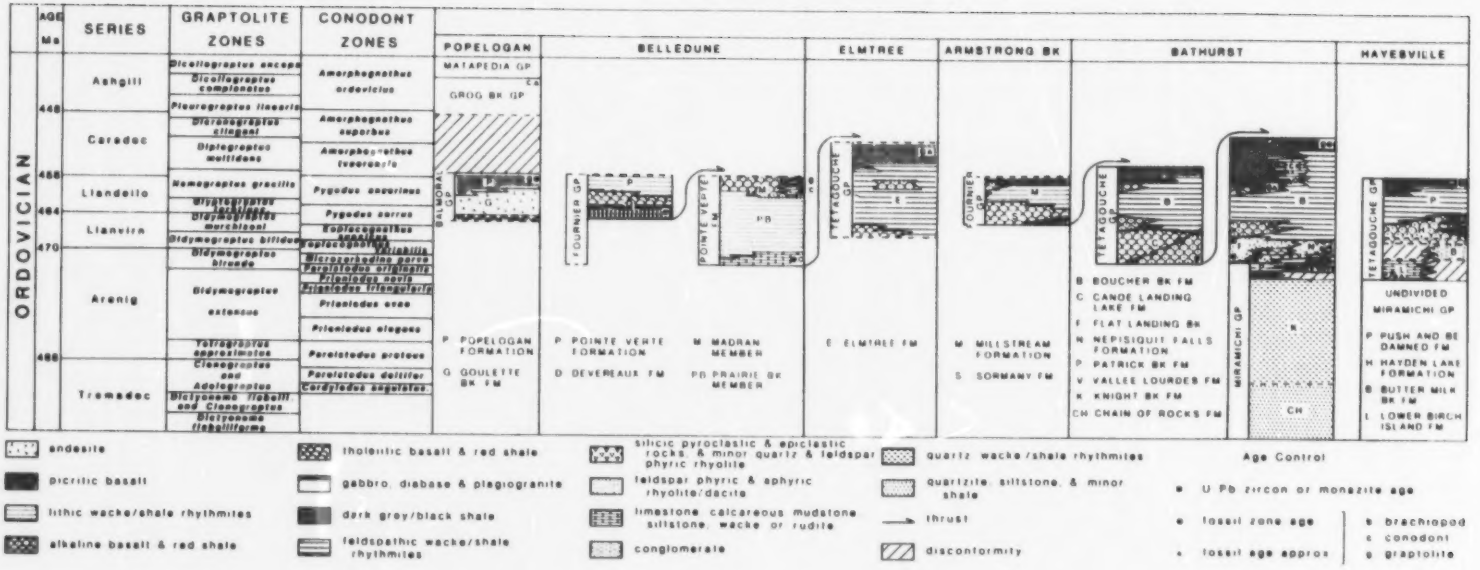


FIGURE 8. Tectonostratigraphy for the Dunnage Subzone of New Brunswick.

structurally below the middle to late Arenigian conodont locality at the base of the Pointe-Verte Formation (Figure 2). On the basis of the lithological similarities to other Caradocian black phyllites, these are also interpreted to be Caradocian in age, since Ashgillian or Llandoverian black phyllites are unknown in northern New Brunswick. The bimodal volcanic rocks in the structurally lower parts of the Elmtree Formation are tentatively interpreted to have a Llanvirnian-early Caradocian age, because all isotopically and paleontologically dated Ordovician volcanic rocks in northern New Brunswick were deposited within this time range (see below), and because of compositional similarities to basalts present in the Tetagouche Group of the Bathurst Subzone (J. Winchester, personal communication, 1988).

A high-strain zone marked by strongly disrupted bedding, mélange and phyllonite separates the Elmtree and overlying Pointe-Verte formations. This zone is also interpreted as a major thrust with older rocks above younger rocks.

POPELOGAN SUBZONE

The Popelogan Subzone, exposed within the Popelogan Anticline (Ruitenberg *et al.* 1977), is a small, elongate inlier of Ordovician rocks that occurs in the Chaleur Uplands approximately 75 km northwest of Bathurst (Figure 1). These rocks were considered to be equivalents of Middle Ordovician rocks within the Miramichi Highlands (Potter 1964). They were later remapped by Irrinki (1976) and Philpott (1987, 1988) and assigned to the Balmoral Group. The lithologic description and stratigraphic division summarized here are taken mainly from Philpott (1987, 1988). The Middle Ordovician Balmoral Group is subdivided into the Popelogan Formation and is composed of black, graptolitic shale and chert, and the Goulette Brook Formation, made up of mafic and ultramafic volcanic rocks. The Popelogan Formation conformably overlies the Goulette Brook Formation and graptolites indicate a late Llandeilian-early Caradocian age (*N. gracilis* zone; Riva, in Philpott 1987). The Popelogan Formation is, therefore, identical in age and lithology to the black slates that occur near the top of the Pointe-Verte Formation. The Goulette Brook Formation is made up of an upper andesitic lapilli tuff member and a lower picritic hyaloclastite member. Volcanic rocks of the Goulette Brook Formation have a chemistry unlike that of any volcanic rocks of the Belledune Subzone or Miramichi Highlands. The Goulette Brook volcanic rocks are interpreted as part of a Middle Ordovician volcanic arc (van Staal *et al.* 1991). The Balmoral Group is disconformably overlain by Ashgillian turbidites of the Grog Brook Group (St. Peter 1978; Nowlan 1983, 1986), marking a short period of erosion and uplift in late Caradocian and/or early Ashgillian times in this area.

ARMSTRONG BROOK SUBZONE

The Armstrong Brook Subzone occurs in the northernmost part of the Miramichi Highlands between a narrow belt of glaucophane- and epidote-bearing blueschists and the Rocky Brook-Millstream Fault (Figure 1). The volcanic rocks of this subzone comprise the Sormany Formation (van Staal *et al.* 1990, 1991) and have been divided into three members; the Armstrong, Murray Brook, and Lincour basalts (Figure 9). The Armstrong Brook basalts are primitive tholeiites with MOR characteristics, including flat REE patterns (van Staal *et al.* 1991). These basalts (Figure 9) have a thin, discontinuous layer of mylonitic gabbro at their base along the contact with the underlying, very highly strained blueschists. The blueschists immediately beneath the Armstrong Brook basalts and gabbro form part of the Murray Brook alkalic basalt suite (Figure 2; van Staal *et al.* 1990), which is chemically similar to the Llandeilian high-Cr alkalic basalts of the Pointe Verte Formation in the Belledune Subzone. The tectonostratigraphy of the Belledune Subzone is thus in part repeated in the Armstrong Brook Subzone (Figure 8). Rocks in the Armstrong Brook Subzone are therefore also interpreted as ophiolitic (van Staal *et al.* 1990, 1991). Structurally higher sheets of basalts, the Lincour basalts, are depleted in high-field-strength-elements (HFSE) and have compositions that are intermediate between MOR-basalts and island-arc tholeiites (van Staal *et al.* 1991). Such basalts with transitional or arc-like compositions are also found at the highest structural levels in the Belledune Subzone and are typical of back-arc environments (Saunders and Tarney 1984). The petrochemistry of the Lincour basalts, thus, supports the earlier interpretation of a back-arc setting proposed by van Staal (1987).

The Lincour basalts are overlain by, and in part interbedded with, quartz- and feldspar-rich lithic wackes and arkoses of the Millstream Formation (van Staal *et al.* 1988b). These are lithologically similar to the wackes of the Pointe-Verte Formation in the Belledune Subzone. The Millstream Formation also includes a few layers of pebble conglomerate (with mainly igneous clasts), lenses of limestone, and black, shaly phyllite with interbedded chert. Although no biostratigraphically diagnostic fossils have been found in the Armstrong

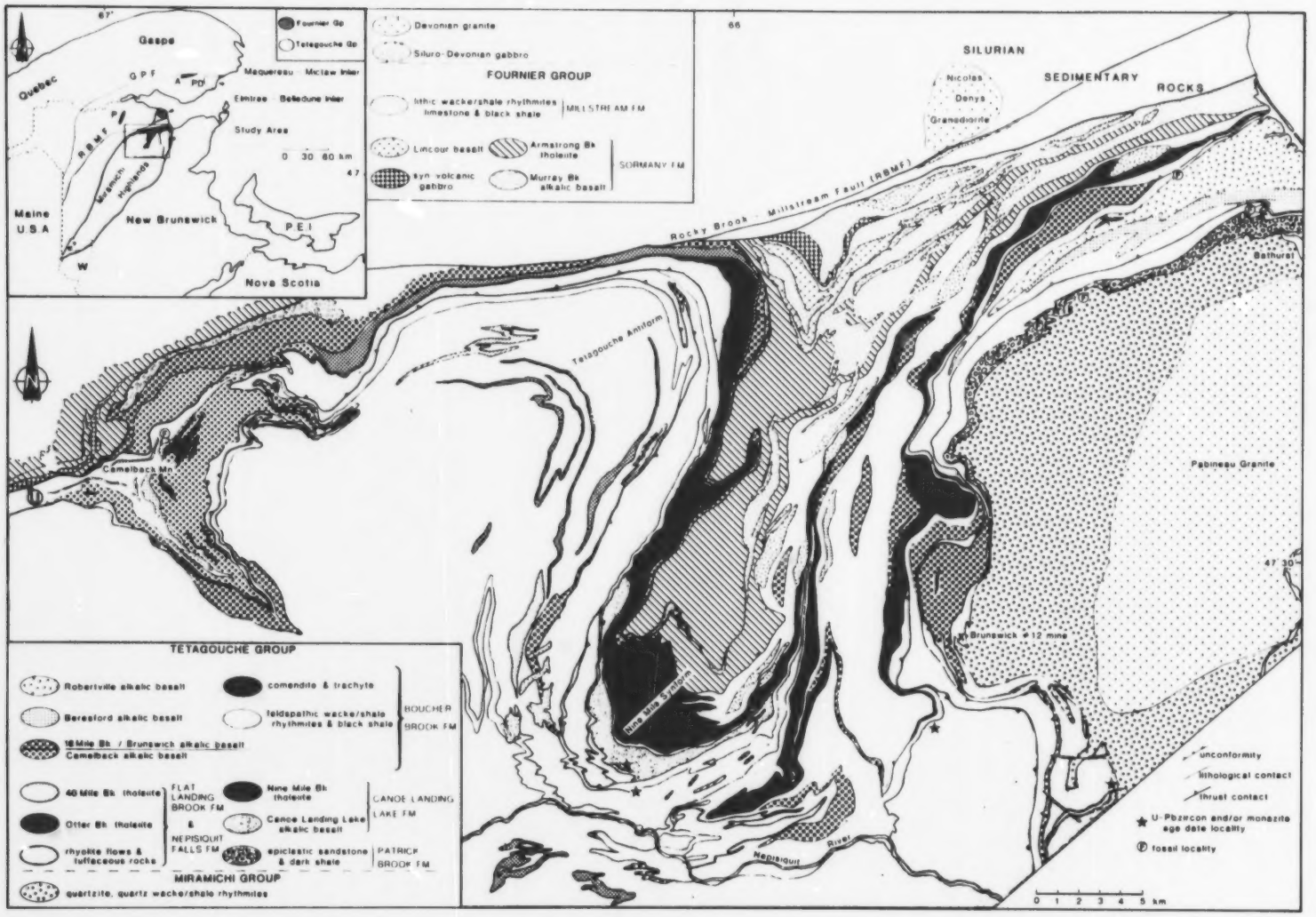


FIGURE 9. Geology of part of the Armstrong Brook and Bathurst subzones in the northern Miramichi Highlands (after van Staal *et al.* 1991). Inset shows the location of the Popelogan (P) Subzone, Arsenault Formation (A), and the Woodstock area (W) with the Oak Mountain Formation arc volcanics.

Brook Subzone, the black phyllites are interpreted as correlatives of the Caradocian, graptolite-bearing, black phyllites in the Belledune and Bathurst subzones (van Staal *et al.* 1988b). The limestone lenses, which are generally closely associated with the black phyllites, are interpreted to have a Llandeilian-early Caradocian age based on: (1) correlation with two small limestone lenses associated with black phyllite of the Boucher Brook Formation, near Camel Back Mountain in the Bathurst Subzone that yielded early Caradocian conodonts (Kennedy *et al.* 1979; Nowlan 1981); and (2) limestone lenses intercalated with basalts in the Pointe-Verte Formation which yielded Llandeilian conodonts (Nowlan 1983). The Armstrong Brook basalts are interpreted to be Llandeilian in age on the basis of the Llandeilian, U-Pb zircon age of the ophiolitic Devereaux Formation, in the Belledune Subzone. If correct, the quartzofeldspathic wackes of the Millstream Formation must also be Llandeilian to Caradocian since they are interbedded with the basalts and, locally, with the black phyllites. This is the same age as similar rocks in the Madran and Prairie Brook members of the Pointe-Verte Formation, but is contrary to earlier speculations suggesting an Ashgillian age for the Millstream Formation (van Staal *et al.* 1988b).

In general, rock types and geochemistry of the basalts in the Armstrong Brook Subzone indicate that they corresponds more closely to rocks found in the Fournier Group than rocks found in the Tetagouche Group. We, therefore, assign the Sormany and Millstream formations to the Fournier Group. An obvious tectonic boundary, marked by the previously mentioned blueschist horizon also supports exclusion of the rocks in the Armstrong Brook Subzone from the Tetagouche Group. Indeed, Young (1911) included volcanic rocks of the Armstrong Brook Subzone near Bathurst within his Fournier Group.

BATHURST SUBZONE

The Tetagouche Group of the Bathurst Subzone is dominated by a large complex of felsic metavolcanic rocks (Figure 9) that have compositions mainly ranging from dacite to rhyolite (Whitehead and Goodfellow 1978; van Staal 1987; Winchester and van Staal 1988). The felsic volcanic rocks comprise a heterogeneous mixture of flows, shallow intrusions, pyroclastic rocks, and proximal epiclastic deposits (van Staal 1987). Local sedimentary structures in the volcaniclastic sedimentary rocks indicate a dominantly subaqueous depositional environment. For mapping purposes, the rocks are generally divided into aphyric or feldspar-phyric rhyolite lavas and minor pyroclastic rocks of the Flat Landing Brook Formation, and mixed epiclastic/pyroclastic sedimentary rocks (tuffites) interbedded with tuffs and quartz and feldspar-phyric rhyolitic sills and/or flows of the Nepisiguit Falls Formation (Figure 10; *cf.*, Skinner 1974; Saif 1977; Davies 1979). Numerous base metal Zn-Pb-Cu-Ag massive sulphide deposits are hosted by, or closely associated with, the felsic volcanic rocks; generally, the tuffites of the Nepisiguit Falls Formation (Smith and Skinner 1958; McAllister 1960; Davies 1966; Harley 1979). Thin, but generally laterally extensive bodies of iron formation (Figure 11), jasper, and a multicoloured (red, purple, green, and black) ferromanganiferous phyllite are commonly associated with the massive sulphides. Clastic sedimentary rocks other than epiclastic volcanic rocks are rare within the felsic volcanic succession.

The felsic metavolcanic rocks also contain two minor suites of tholeiitic basalt, either in the form of sills and dykes or as massive and pillowed flows, pyroclastic tuffs, breccias and agglomerates. These basalt suites are referred to as the Otter Brook and Forty Mile Brook tholeiites, and have compositions similar to continental tholeiites (van Staal *et al.* 1991). Basaltic agglomerates of the Otter Brook suite contain fragments of the surrounding felsic volcanic rocks into which compositionally similar dykes are intruded. The Otter Brook basalts were probably extruded contemporaneously with, or shortly after, deposition of the oldest felsic volcanic rocks. Pillows, common in all other basalt suites in the northern Miramichi Highlands, have never been observed among the Otter Brook basalts, possibly indicating a subaerial environment of deposition. If correct, at least some volcanic edifices must have been emergent at the time of their formation. Weathering of these subaerially exposed felsic volcanic edifices would also provide a simple explanation for the abundance of volcanic detritus in associated and coeval sedimentary rocks of the Patrick Brook and Boucher Brook formations (Figure 8). Such an environment is not necessarily in conflict with the subaqueous depositional environment deduced for most of the felsic volcanic rocks (van Staal 1987), since the fossils and sedimentary structures found in interbedded iron formation and epiclastic, tuffaceous sedimentary rocks are consistent with a shallow water environment. These include stromatolite-like structures and ooids in carbonate facies iron formation (McMillan 1969; Saif 1980; van Staal 1987), and brachiopods and pelecypods in shaly sediments (Bolton 1968; Fyffe 1976; Gummer *et al.* 1978; Neuman 1984). Pelecypods occurring in tuffaceous and/or epiclastic sedimentary rocks that host the Devils Elbow (Bolton 1968) and Taylor Brook (Gummer *et al.* 1978),

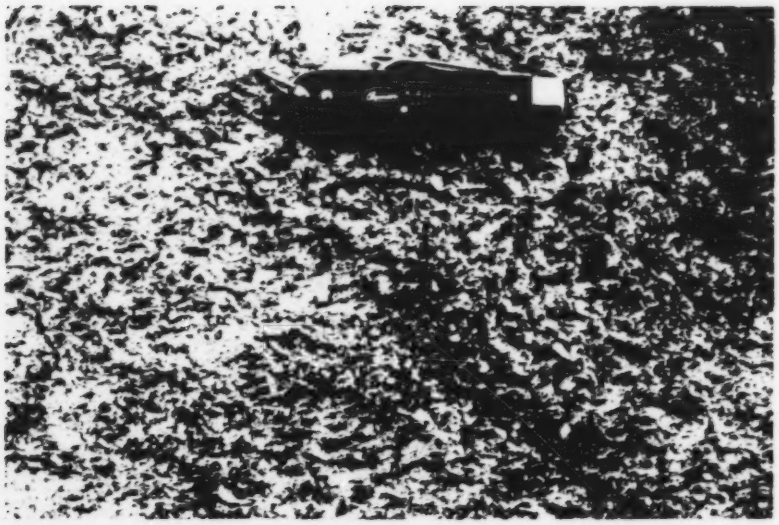


FIGURE 10. Quartz and feldspar-phyric intrusion or flow in the Nepisiguit Falls Formation at Devils Elbow, Tetagouche Group, Bathurst Subzone.

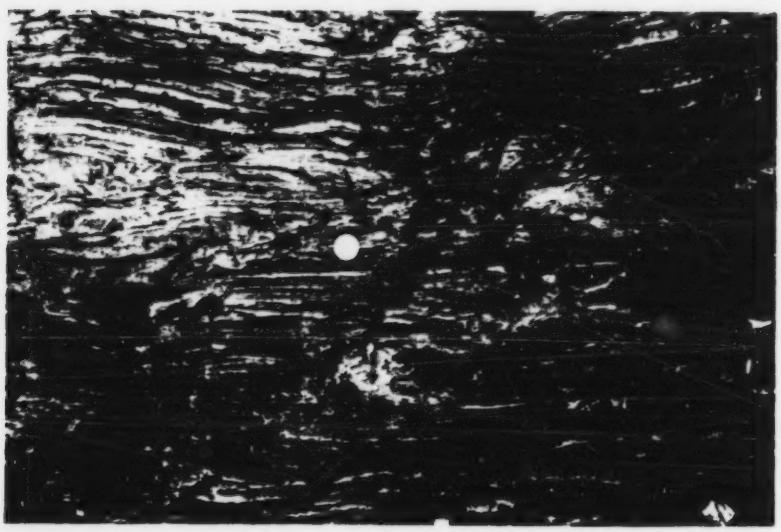


FIGURE 11. Upright, shallowly plunging F_2 fold in banded oxide-jasper iron formation at the top of the Nepisiguit Falls Formation, Tetagouche Group, Bathurst Subzone.

massive sulphide deposits are not biostratigraphically diagnostic (Pojeta, written communication, 1988). It is possible that these pelecypods represent unique faunas occurring only around hydrothermal vents. U-Pb zircon ages of 469 ± 2 Ma for a crystal tuff of the Nepisiguit Falls Formation and 466 ± 5.3 Ma for a spherulitic rhyolite at the top of the Flat Landing Brook Formation (Sullivan and van Staal 1990) indicate a Llanvirnian to early Llandeilian age for the felsic volcanism (Figure 8). A similar age range, based on a few critical fossil localities and regional correlations, is deduced for felsic volcanic activity in central New Brunswick (Fyffe *et al.* 1983).

The Nepisiguit Falls Formation conformably overlies rocks of the Vallée Lourdes Formation (Figure 8; van Staal *et al.* 1988b) below Tetagouche Falls and near the mouth of the Tetagouche River close to the town of Bathurst. The Vallée Lourdes Formation comprises cross-bedded calcarenites (Figure 12), calcareous siltstones, and conglomerates (Figures 13, 14). This Formation can be traced as lenses rather than as a continuous unit for more than 15 km southwestward from the town of Bathurst. Both the Vallée Lourdes and the Nepisiguit Falls Formation are locally underlain and overlain by tuffaceous sandstones and dark shales of the Patrick Brook Formation (Figures 15, 16) indicating that these formations interfinger lithostratigraphically (Figure 8). The Vallée Lourdes Formation yielded middle Arenigian to earliest Llanvirnian conodonts and brachiopods near Tetagouche Falls (Fyffe 1976; Nowlan 1981; Neuman 1984) and at least in part represents shallow water deposits. These ages show that the Vallée Lourdes Formation is older than the conformably overlying formations as deduced from fossils and isotopic age determinations (van Staal *et al.* 1990). The data set an upper limit to the age of the Miramichi Group, which must be Lower Ordovician or older. Lithological correlatives of the Vallée Lourdes Formation (Figure 8) in central New Brunswick (Lower Birch Island Formation of the Hayesville Subzone) also contain brachiopods and conodonts suggesting a middle to late Arenigian age (Poole 1963; Neuman 1968; Nowlan 1981), but the conodonts may extend into the earliest Llanvirnian (Nowlan 1981). The brachiopods and conodonts belong to the Celtic and North Atlantic biogeographic provinces, respectively (Nowlan 1981); indicating a paleogeographic setting distant from the North American craton.

Understanding the relationships between the Dunnage Zone equivalents, *i.e.*, Tetagouche Group, and the Gander Zone equivalents, *i.e.*, the Miramichi Group, is critical to the tectonic interpretations of the northeastern Appalachians. Since the lowest parts of the Tetagouche Group, *i.e.*, Vallée Lourdes Formation, represent in part shallow-water deposits that disconformably overlie the relatively deep-water turbidites of the Miramichi Group (Ruitenberg *et al.* 1977), either the contact between these two groups is tectonic or some relative uplift has taken place in the Early Ordovician. A disconformity between the Vallée Lourdes Formation and the Miramichi Group is marked by a thin layer of conglomerate east of Tetagouche Falls, 12 km west of Bathurst. The conglomerate contains well-rounded quartzite and phyllite pebbles derived from the underlying Miramichi Group (Figure 17), indicating uplift and local erosion of the Miramichi Group before deposition of the Tetagouche Group. Omission of the Vallée Lourdes Formation and the presence of a phyllonite along most Miramichi-Tetagouche contacts indicate that the original stratigraphic relationships between the groups has been tectonized subsequently. Quartzite and phyllite pebbles derived from the Miramichi Group are locally abundant in felsic agglomerates of the Flat Landing Brook Formation (Davies 1972a, b), suggesting that the felsic volcanic magma came up through crust underlain by the Miramichi Group. Other indications that both the Miramichi and Tetagouche groups were underlain by a common continental crust are; (1) the presence of Middle Ordovician peraluminous granites (Fyffe *et al.* 1977; Whalen 1987; Bevier 1988) in areas underlain by the Miramichi Group, (2) the fact that the granites intruded locally consanguineous felsic volcanic rocks (Whalen 1987) of the Tetagouche Group, and (3) the dominance of felsic volcanic over mafic volcanic rocks.

A conglomerate similar to the basal Vallée Lourdes Formation occurs locally at the base of the Tetagouche Group in central New Brunswick (see Buttermilk Brook Formation of the Hayesville Subzone) and in Maine at the contact between the Grand Pitch and Shin Brook formations (Neuman 1967). In Maine, this conglomerate marks the Penobscot unconformity of Neuman (1967, 1968) and it is the principal evidence for the Early Ordovician Penobscot Orogeny in the central part of the northern Appalachians. There are several independent lines of evidence for the existence of the Penobscot Orogeny and its Ganderian equivalent in Newfoundland (Kennedy 1975; Boone and Boudette 1989; Williams and Piasecki 1990; van Staal and Williams 1991). However, structural analysis in New Brunswick indicates that the rocks below and above the conglomerate display the same structural history and there is no convincing evidence for a predepositional

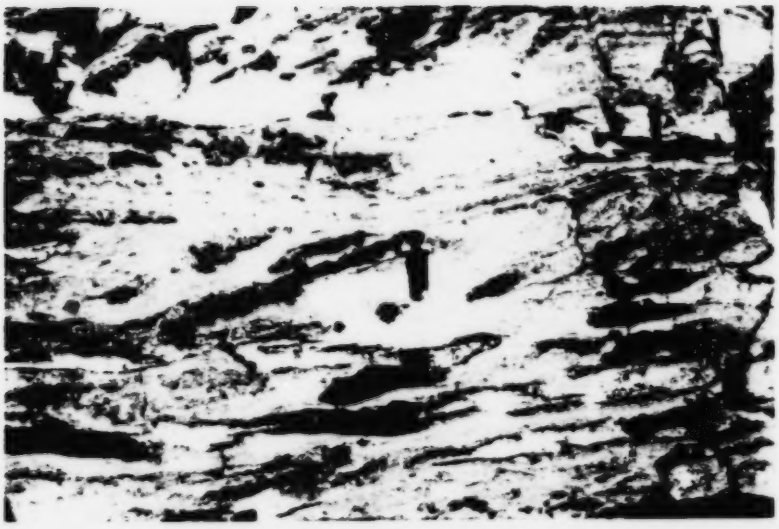


FIGURE 12. Cross-bedded, sandy limestone of Vallée Lourdes Formation, Tetagouche Group, Bathurst Subzone.

FIGURE 13. Thin-bedded calcareous siltstone of the Vallée Lourdes Formation, Tetagouche Group, Bathurst Subzone.

FIGURE 14. Boulders of granitic gneiss in tuffaceous limestone of the Vallée Lourdes Formation, Bathurst Subzone.

FIGURE 15. Angular felsic clasts in feldspathic wacke of the Patrick Brook Formation, Tetagouche Group at Tetagouche Falls, Bathurst Subzone.

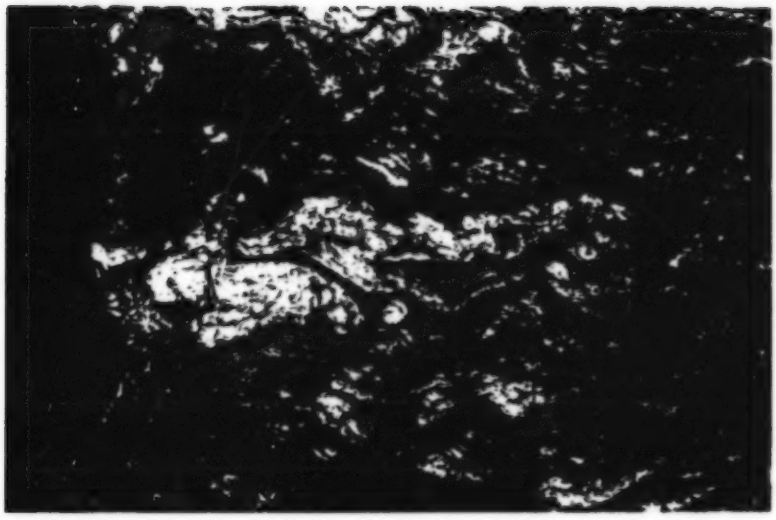


FIGURE 16. Northeast-trending F_3 crenulations refolding isoclinal F_2 folds within tuffaceous phyllite of the Patrick Brook Formation, Tetagouche Group, Bathurst Subzone. Note well-developed S_1 differentiated layering in the tuffaceous rocks, which is folded by F_2.

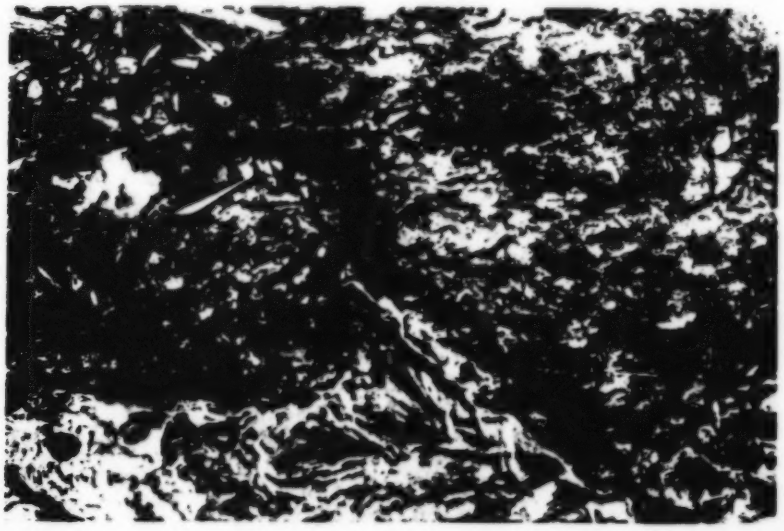


FIGURE 17. Quartz wacke pebbles in sandy limestone at the base of Vallée Lourdes Formation, Tetagouche Group, Bathurst Subzone.

cleavage in pebbles derived from the Miramichi Group. Furthermore, structural contrasts between the Shin Pond and Grand Pitch formations are debatable, since contrasts in competency may explain an abundance of tight, second order mesoscale folds in the multilayered Grand Pitch Formation and their scarcity or absence in the more massive and competent Shin Brook Formation. The conglomerate at the base of the Tetagouche Group and the Shin Brook Formation marks a phase of uplift, which at least locally caused emergence of the Miramichi Group. This was apparently unrelated to penetrative deformation and immediately preceded extrusion of back-arc volcanic rocks (van Staal *et al.* 1991). The unconformity probably represents lithospheric doming associated with the onset of back-arc rifting during the middle to late Arenigian (Figure 18; Stage A).

Although a part of the felsic volcanic rocks in the Bathurst Subzone are interpreted to be autochthonous or parautochthonous with respect to the underlying clastic sedimentary rocks of the Miramichi Group, most volcanic rocks are interpreted to be allochthonous (van Staal *et al.* 1990; Figures 8, 9). The structurally lowest part of the succession consists of imbricated rocks of the Flat Landing Brook, Nepisiguit Falls, and Boucher Brook formations, which are structurally overlain by two major thrust sheets containing rocks of the Canoe Landing Lake Formation (Figures 8, 9). The structurally lowest of these two thrust sheets consists mainly of pillowed, primitive alkalic basalts of the Canoe Landing Lake suite with minor intercalations of comendite and rhyolite, all interbedded with abundant red shale and chert. The overlying thrust sheet mainly consists of distinctive tholeiitic pillow basalts of the Nine Mile Brook suite interlayered with minor flows of alkalic basalts, red shale and chert. The alkalic basalts are compositionally identical to those in the Canoe Landing Lake suite (van Staal *et al.* 1991).

Narrow zones of phyllonites and mylonites, recording relatively high strains (van Staal 1986, 1987), are present at the base of each thrust sheet and outline major truncations of units (Figure 9). The volcanic formations of each thrust sheet are overlain by a remarkably similar package of dominantly sedimentary rocks that comprise thin-bedded feldspathic wacke, multicoloured shale, and three minor suites of alkalic basalt with trachyandesitic and comenditic differentiates (Figure 9; van Staal *et al.* 1991). This largely sedimentary unit comprises the Boucher Brook Formation (Figure 8). The black shale yielded Caradocian graptolites in three localities (van Staal *et al.* 1988b), the youngest of which belongs to the *D. clingani* or *C. spiniferus* zone (Riva and Malo 1988). One trachyandesite yielded a U-Pb zircon age of 457 ± 1 Ma (R. Sullivan, personal communication, 1990), and confirms the Llandeilian-Caradocian age of the Boucher Brook Formation inferred from paleontological and other isotopic evidence (Sullivan and van Staal 1990; Figure 8). The presence of red shale and the similarities in age of zircons and monazites (van Staal and Sullivan, in preparation), in each of the volcanic dominated formations indicates that the thrust sheets span the same short age range, the volcanic base being slightly older than the sedimentary top (Figure 8). When imbricated, this places older rocks over slightly younger rocks.

Detailed geochemistry of over 200 samples (van Staal *et al.* 1991) indicates that the volcanics of the Tetagouche Group represent a continental margin, rift sequence, produced in late Arenigian/Llanvirnian times during the opening of an ensialic back-arc basin, which subsequently developed into a marginal sea floored by oceanic crust (van Staal 1987; Fyffe *et al.* 1990; van Staal *et al.* 1991). Zircon xenocrysts (L. Heaman, written communication, 1988) recovered from the youngest alkalic basalts (Figure 19) of the Boucher Brook Formation lend further support to the interpretation that at least part of the Tetagouche Group was underlain by continental crust during deposition.

HAYESVILLE SUBZONE

Middle Ordovician volcanic rocks of the Tetagouche Group occur throughout the central and southern parts of the Miramichi Highlands (Poole 1963; Potter 1969; Venugopal 1978, 1979, 1981; Lutes 1979; Irrinki 1980; Crouse 1981; Fyffe 1982a, b). In general, the Ordovician stratigraphy in the Hayesville Subzone (Figure 1) is similar to that in the Bathurst Subzone of the northern Miramichi Highlands, except that mafic rocks are more abundant than felsic rocks. Geochemical studies of the mafic volcanic rocks in central New Brunswick (Fyffe *et al.* 1981) support this correlation. The stratigraphic sequence in the Hayesville area of central New Brunswick (Figure 8) is best exposed along the Southwest Miramichi River on the southeastern flank of a northeasterly plunging anticline. Although outcrop is virtually continuous, the actual contact between the quartzose clastic rocks of the Miramichi Group and overlying carbonate-rich rocks of the Tetagouche Group is not exposed. Nonetheless, bedding attitudes suggests a conformable relationship. This relationship can be confirmed along strike to the southwest on Middle Hayden Brook where continuous stream-bed exposures reveal a gradational

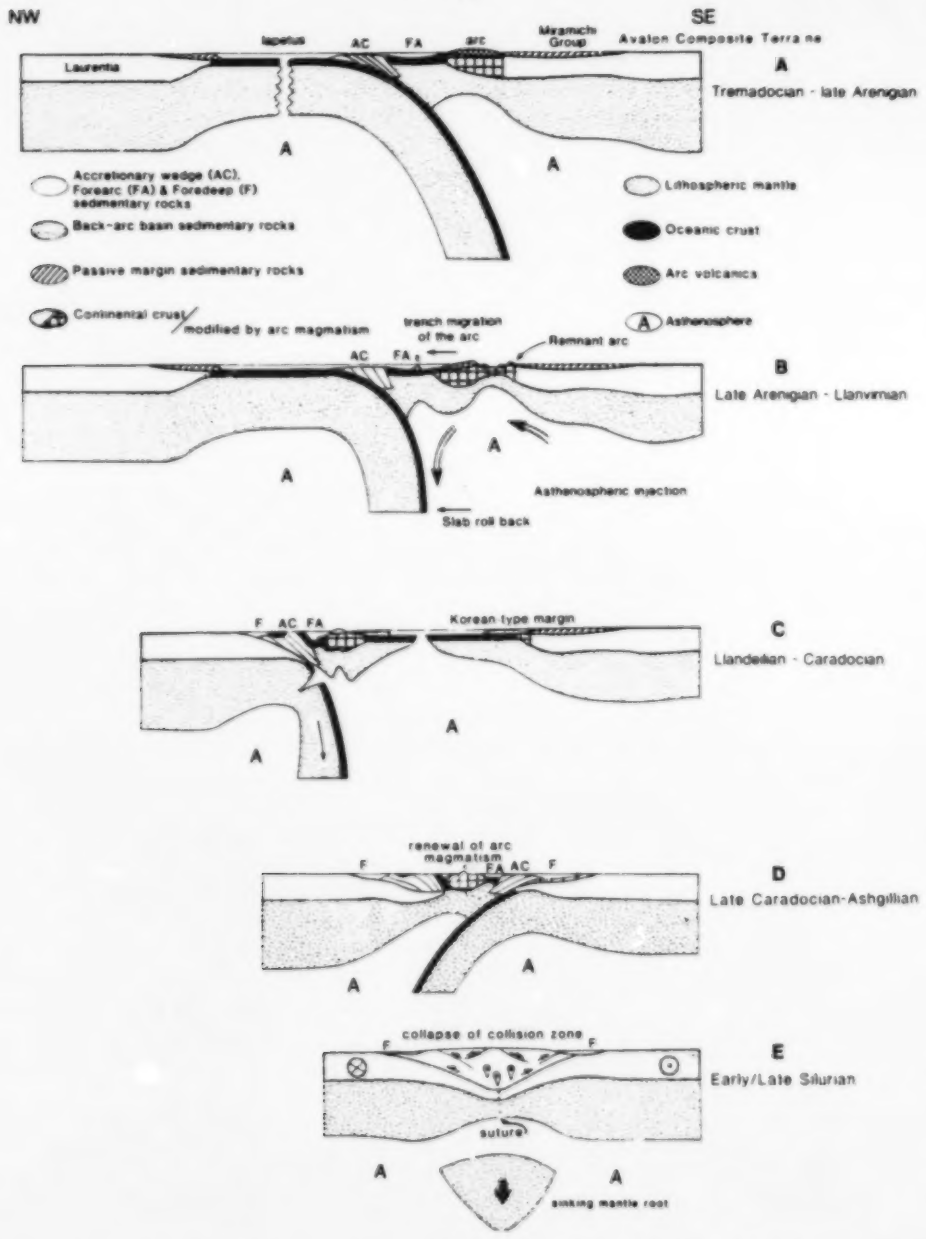


FIGURE 18. Schematic model of the tectonic evolution of the northern Appalachians in New Brunswick and adjacent Quebec. Adapted and expanded after van Staal *et al.* (1991). Although not shown, this model does not exclude earlier accretions of volcanic arcs (*e.g.*, Taconic arc) to Laurentia; neither does it show the kinematic evolution of the Penobscotian or Ganderian orogeny, which was probably responsible for accretion of the Annidale Belt and GRUB in Newfoundland to the Gander Zone. Stages A, B, and C see van Staal *et al.* (1991). Stage D Closure of back-arc basin by northwest-directed subduction following a polarity reversal induced by the collision between the Popelogan arc and Laurentia. Late Ordovician/Early Silurian volcanism in adjacent Quebec (David and Gariepy 1990) was probably initiated by this new Benioff zone. First arrival of the rocks of the Korean-type passive margin in the subduction zone probably took place in the Ashgillian. Stage E Delamination by convective removal of the lithospheric mantle root, which leads to uplift and collapse of the collision zone.

change from olive-green siltstone and shale of the Miramichi Group into fossiliferous calcareous beds of the Tetagouche Group.

The Tetagouche section exposed on the Southwest Miramichi River begins with calcareous siltstone of the Lower Birch Island Formation (Figure 20). The siltstone is about 30 m thick and contains thin felsic tuff beds and numerous brachiopods dated as middle to late Arenigian (Neuman 1968, 1984). The Lower Birch Island Formation is overlain by 500 m of red, green, and black phyllite of the Hayden Lake Formation (Poole 1963; Potter 1969). A 1 m thick bed of red grit at the base of the Hayden Lake Formation contains clasts of the underlying calcareous siltstone indicating a local post-Arenigian erosional break (Irrinki 1980). A period of extensive uplift is evident farther to the northwest on the limb of an adjacent synform where conglomerate of the Buttermilk Brook Formation directly overlies the Miramichi Group (Potter 1969; Crouse 1981) in place of the Lower Birch Island Formation. The conglomerate contains rounded cobbles of quartz wacke derived from the underlying Miramichi Group. Abundant mafic and lesser felsic volcanic rocks, are typically interbedded with the Hayden Lake Formation. The felsic volcanic rocks are mainly trachytes and typically associated with alkalic basalts. Extrusion of these volcanics apparently coincided with the onset of uplift recorded by the Buttermilk Brook Formation. Graptolites of the *G. terretiusculus* zone from black shale of the Hayden Lake Formation and of the *N. gracilis* zone from volcaniclastic wackes of the overlying Push and Be Damned Formation (Figure 21), and Belle Lake Formation of the Woodstock area, 100 km to the southwest, confirm the Llanvirnian-Llandeilian age of volcanism throughout the Miramichi Highlands (Potter 1969; Fyffe *et al.* 1983, 1988a).

In the Woodstock area, black shales of the Bright Eye Brook Formation of the Miramichi Group (new name after brook flowing into Eel River) contain late Tremadocian to middle/late Arenigian graptolites (Fyffe *et al.* 1983). The Bright Eye Brook Formation conformably underlies felsic and mafic volcanic rocks of the Oak Mountain Formation of the Tetagouche Group (formerly referred to as Pocomoonshine volcanics). These volcanics have calc-alkalic affinities and were interpreted as part of an ensialic arc by Dostal (1989). They are intruded by the Benton granodiorite, which is lithologically and compositionally identical to the closely associated late Arenigian Gibson granodiorite (U-Pb zircon age of 473 ±1 Ma; Bevier 1990). These two plutons contain porphyry Cu-type mineralization and they are possibly connected at depth (Fyffe 1982a). The Oak Mountain Formation volcanics are therefore probably, at least in part, middle to late Arenigian in age. They are interpreted as the remnants of a Lower Ordovician ensialic arc that was subsequently rifted in late Arenigian/Llanvirnian times (van Staal *et al.* 1991). The boundary between the conformable Miramichi and Tetagouche groups in this area is placed at the first occurrence of volcanic rocks. The Oak Mountain Formation is overlain by the Belle Lake Formation, which yielded graptolites of the *N. gracilis* zone (Fyffe *et al.* 1983). Conodonts of the *P. serrus-P. anserinus* zone (Llanvirnian/Llandeilian boundary; Nowlan 1981; St. Peter 1982) were extracted from the Waterville limestone member of the Belle Lake Formation (Venugopal 1979). The conodont fauna of the Waterville limestone is identical to that of the Cobbs Arm limestone in the Exploits Subzone of Newfoundland (Nowlan 1981).

The contacts between the Tetagouche Group and the post-Middle Ordovician cover are generally faulted; however, an unconformity separates Middle Ordovician limestone from late Ashgillian conglomerate in the Becaguimec River area northeast of Woodstock (St. Peter 1982) and Late Silurian to Early Devonian conglomerate overlies quartz sandstone of the Miramichi Group southwest of Woodstock (Venugopal 1979; Lutes 1979).

Structures of the New Brunswick Dunnage Zone are similar to those of the New Brunswick Gander Zone and they are described in a following section on the New Brunswick Gander Zone. Because rocks of the New Brunswick Dunnage and Gander zones are linked stratigraphically, a tectonic model that rationalizes all relationships is developed after the descriptions of the New Brunswick Gander Zone.

GANDER ZONE

INTRODUCTION

The New Brunswick Gander Zone is characterized by a thick, complexly deformed sequence of Cambrian-Ordovician quartz sandstones and pelite that is lithologically similar to the Gander Group (Kennedy 1976) of Newfoundland. These quartzose rocks constitute the Miramichi and Cookson groups in the Miramichi and St. Croix subzones, respectively. The stratigraphy of the Miramichi Highlands or Miramichi Terrane (Fyffe and Fricker 1987) has previously been compared solely to that of the Gander Zone in Newfoundland (Rast *et al.* 1976), but the integral association of voluminous Ordovician volcanic rocks in northeastern New Brunswick gives the region character-

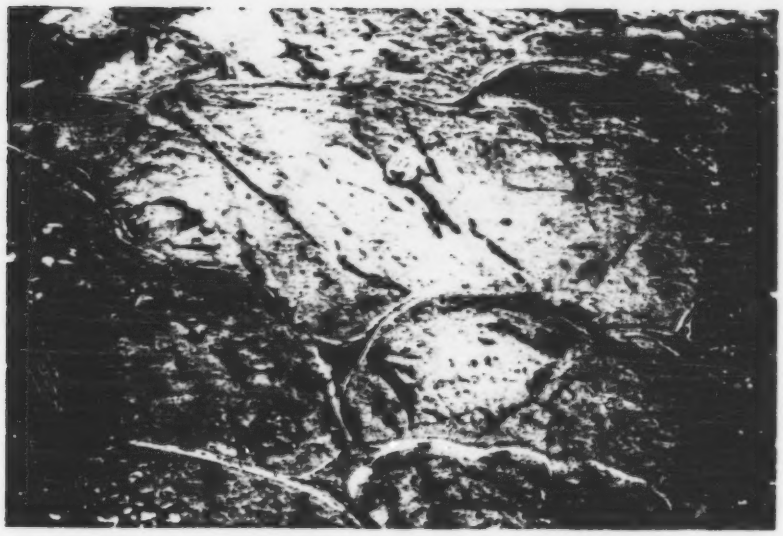


FIGURE 19. North-younging pillows in Beresford alkalic basalt of the Boucher Brook Formation, Tetagouche Group, Bathurst Subzone.

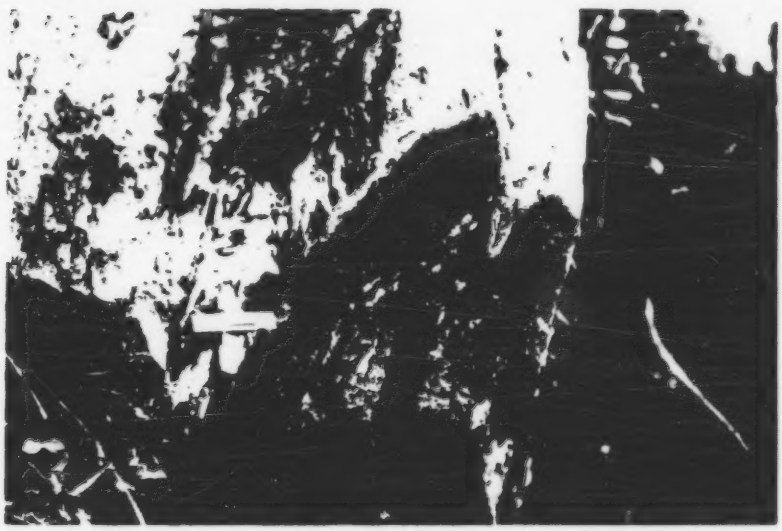


FIGURE 20. Tightly folded, fossiliferous, calcareous siltstone of the Lower Birch Island Formation, Tetagouche Group, Hayesville Subzone.

istics of both the Gander and Dunnage zones (Fyffe 1977; van der Pluijm and van Staal 1988). In order to correspond with established tectonostratigraphic nomenclature from Newfoundland, the Cambrian-Ordovician clastic sequence of the Miramichi Highlands is included in the Gander Zone as the Miramichi Subzone, while the younger volcanic sequence is included in the Dunnage Zone (Figure 1). High-grade metamorphic complexes in the central Miramichi Highlands have been interpreted as crystalline basement to the clastic sequence by analogy with the Gander Zone of Newfoundland (Rast *et al.* 1976), although no definite basement is known in Newfoundland. Recent U-Pb geochronology has shown that at least the intrusive components of these complexes in New Brunswick are Ordovician in age (Fyffe *et al.* 1988a).

The Gander Zone of New Brunswick is also considered to include the St. Croix Terrane (Fyffe and Fricker 1987) or St. Croix Subzone to the southeast. This extension of the New Brunswick Gander Zone differs from that of Rast *et al.* (1976), who included only rocks of the Miramichi Highlands. The stratigraphy within the St. Croix Subzone correlates well with that of the Newfoundland Gander Zone in that both contain an abundance of clastic sedimentary rocks with relatively minor volcanic rocks, intruded by garnet-muscovite-bearing granites. The St. Croix Subzone extends the Gander Zone of New Brunswick southward to the Avalon Zone boundary and, thus, corresponds with its limits in Newfoundland. This boundary in New Brunswick is mainly hidden by Silurian to Early Devonian volcanic and sedimentary rocks of the Mascarene Belt. The St. Croix Subzone is separated from the Miramichi Subzone by Silurian turbidites of the Fredericton Belt (Figure 1). A wedge of complexly deformed pelite and psammite of Gander aspect (Figure 1) has recently been recognized along the Fredericton Fault, which transects the central portion of the Fredericton Belt (Fyffe 1988).

MIRAMICHI SUBZONE

The Miramichi Group (previously informally referred to as lower Tetagouche Group) in the northern part of the Miramichi Highlands is represented by the Knights Brook Formation (new name after brook flowing into Nepisiguit River, east of the Nepisiguit Falls) and the Chain of Rocks Formation (new name after rapids on Nepisiguit River). The Knights Brook Formation consists of dark grey to black, locally graphitic shales, rhythmically interbedded with medium- to thick-bedded, light grey to olive-green, graded quartz sandstones (Figure 22). The Chain of Rocks Formation compositionally and texturally similar to the Knights Brook Formation, but does not contain the dark grey to black shales (Figure 23). The Knights Brook Formation structurally overlies the Chain of Rocks Formation. The boundary is placed where the black shale beds disappear and are replaced by more siltier greenish grey phyllites (*cf.*, Helmstaedt 1971; van Staal *et al.* 1988b). Although no fossils have been found in either the Knights Brook or Chain of Rocks formations, Tremadocian to middle/late Arenigian graptolites were discovered in the Bright Eye Brook Formation, a lithologic correlative of the Knights Brook Formation in the Woodstock area of west-central New Brunswick (Fyffe *et al.* 1983).

Black slates of the Bright Eye Brook Formation conformably overlie olive-green quartz wackes and light green shales that are interbedded locally with maroon and green siltstones and shales. Grading locally varies from inverse at the base of a bed to normal in the rest of the bed. Current ripples, flame structures, and sole marks are present locally (Figure 24). Similar turbidites along strike in the Danforth area of adjacent Maine are known as the Baskahegan Lake Formation (Ludman 1987).

The greenschist-facies quartz sandstones and shales in the central Miramichi Highlands (correlatives of the Knights Brook and Chain of Rocks formations) pass westward through a steep metamorphic gradient into amphibolite-facies rocks of the Trousers Lake Complex (Skinner 1975; Fyffe and Pronk 1985; Fyffe *et al.* 1988a). This complex has been traced south-southeastward from the Trousers Lake area to the Catamaran Fault, where it is dextrally offset by a few kilometres, and thence continues southward to the western part of the Hayesville area. The Trousers Lake Complex is characterized by thin-banded fine-grained amphibolites which contain dark green hornblende-rich bands alternating with light grey plagioclase-rich bands. The amphibolites are interlayered with cordierite-andalusite-bearing pelites and psammites, and with granitic gneiss containing microcline augen. Locally, partial melting of the psammitic and pelitic beds has progressed to the extent that the more competent amphibolite layers occur as isolated rafts within the mobilized, sillimanite-bearing host (St. Peter 1981). Although originally interpreted as Precambrian basement to the Miramichi Group (Rast *et al.* 1976), U-Pb ages of 451 +15/-1 Ma and

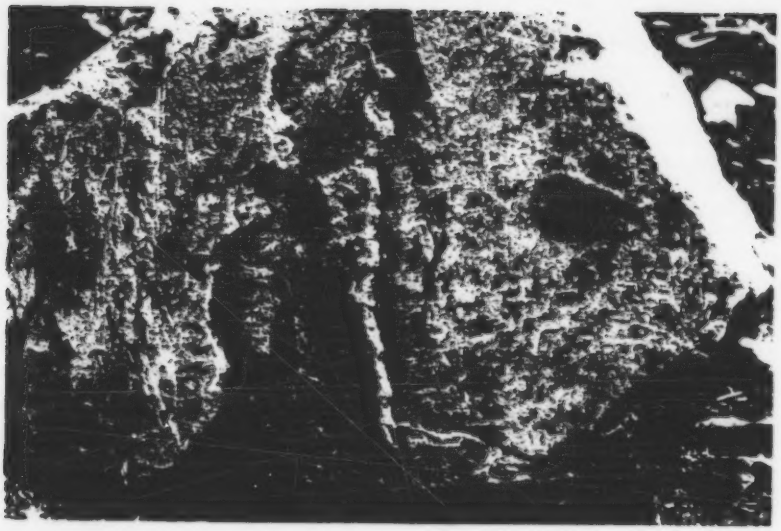


FIGURE 21. Lithic wacke of Push and Be Damned Formation containing rip-up clasts of dark grey siltstone, Hayesville Subzone.

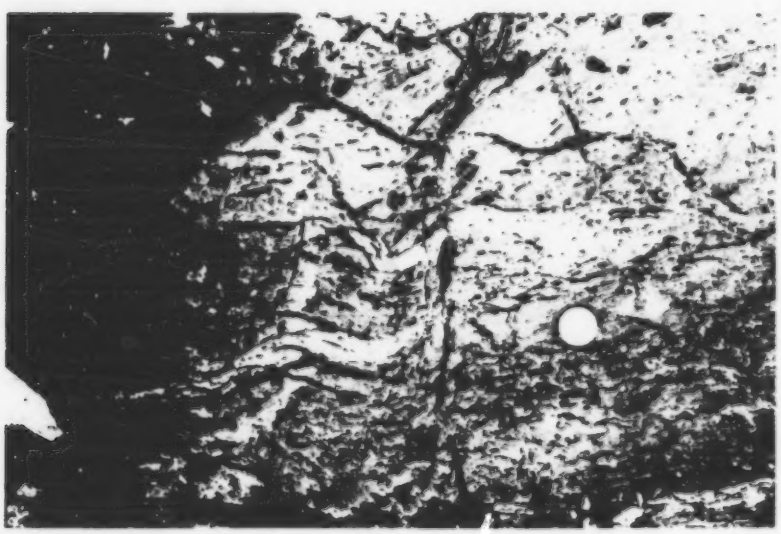


FIGURE 22. Interference pattern between upright F_2 fold (folds F_1) and northeast-trending open F_3 fold within phyllites of the Knights Brook Formation, Miramichi Subzone.

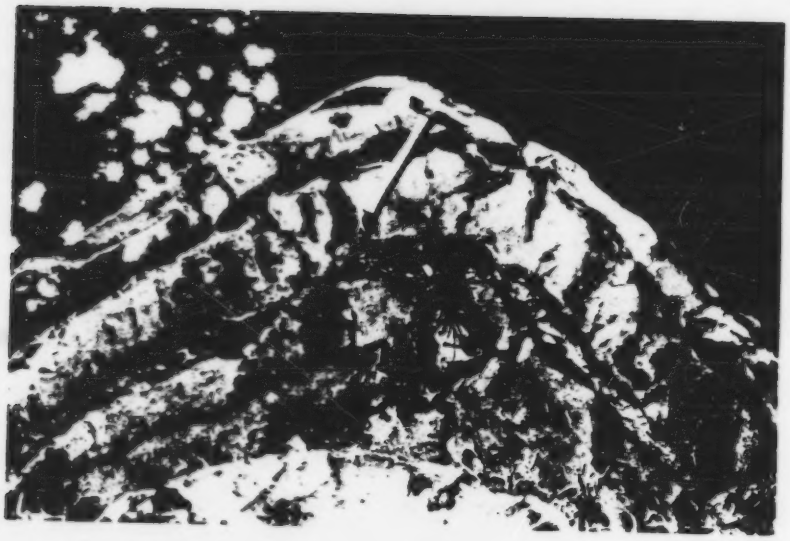


FIGURE 23. Steeply plunging F_2 fold in medium-bedded quartz wacke of the Chain of Rocks Formation, Tetagouche Group, on Middle River, Miramichi Subzone.

FIGURE 24. Sole marks in quartz wackes of the Miramichi Subzone.

434 +29/-6 Ma have recently confirmed previously published Ordovician Rb-Sr ages for the granitic gneisses of the complex (Fyffe *et al.* 1988a).

ST. CROIX SUBZONE

The St. Croix Subzone of southern New Brunswick underlies a northeast-southwest-trending belt that extends from Canaan River, 50 km west of Moncton, southwestward to St. Stephen on the border with Maine. Its extension into Maine, although interrupted by numerous Devonian plutons, can be traced over 100 km to the Penobscot Bay area (Ludman 1987). Ruitenberg (1967) separated rocks in the St. Croix Highlands into Silurian and Ordovician successions, and included the Ordovician rocks in the Cookson Formation, named after exposures on Cookson Island at the head of Oak Bay. Ludman (1987), mapping on the Maine side of the border, elevated the formation to group status and established new formations within it. These have been extended into the St. Stephen area of New Brunswick and their stratigraphic order revised by Fyffe and Riva (1990).

The Calais Formation, the lowermost unit of the Cookson Group, comprises black carbonaceous slate interstratified with minor thin-bedded wacke. A pillowed basalt member, about 100 m thick, occurs near the top of the formation (Figure 25). The flows have been thermally metamorphosed to a plagioclase-actinolite-biotite-sphene-iron oxide assemblage during emplacement of nearby Devonian gabbroic plutons. The basalt is moderately evolved with trace-element abundances similar to some passive continental margin tholeiites (Fyffe *et al.* 1988b). Black slates in the contact aureoles contain abundant cordierite and andalusite porphyroblasts. A thick sandstone-rich sequence, conformably overlying the Calais Formation, is divided into three formations. The Woodland Formation contains rhythmically interstratified, thin- to medium-bedded (2-20 cm), quartzofeldspathic wacke and slightly to highly carbonaceous slate (Figure 26). The wacke is well-graded and about as equally abundant as the slate. The Digdeguash Formation comprises interbedded dark grey slate, greenish grey quartz wacke, lithic wacke, and granule conglomerate containing abundant volcanic clasts (Figure 27). Although assigned to the Silurian by Ruitenberg (1967), it is considered by Fyffe and Riva (1990) to be a facies of the Woodland Formation. The overlying Kendall Mountain Formation is mainly thin- to thick-bedded (10 cm-2 m), quartzose arenite with interbeds of siltstone, black slate conglomerates, and mafic volcanic rocks (Figure 28). The Kendall Mountain Formation is estimated to be between 500 to 700 m thick and the Woodland Formation, about 800 m thick (Ludman 1987).

The Basswood Ridge-Pendar Brook Fault separates the St. Croix Subzone from Silurian wackes of the Fredericton Belt to the northwest. An unconformity between the Calais Formation and Silurian conglomerate of the Oak Bay Formation is exposed on Cookson Island in the southeast. The graptolite *Clonograptus herrmanni* found immediately beneath the unconformity provides an Early Ordovician (Tremadocian) age for the Calais Formation (Cumming 1967). Graptolites from black slate of the Kendall Mountain Formation belong to the *Climacograptus wilsoni* Zone of the Caradocian (Fyffe and Riva 1990). The Cookson Group has been lithologically correlated with the Miramichi Group (Rast and Stringer 1974; Fyffe *et al.* 1983). It has also been correlated with parts of the Saint John Group of the Avalon Zone (Ludman 1987), although this has been disputed (Fyffe and Pickerill 1986). Equivalents in coastal Maine are the Megunticook and Penobscot formations (Ruitenberg and Ludman 1978; Ludman 1987).

The St. Croix Subzone to the northeast of the Saint John River contains a thick, steeply dipping volcanic succession (Annidale belt) of Dunnage affinity that, on the basis of rare facing evidence, appears to young to the southeast (McLeod *et al.* 1990). In the lower part of the volcanic pile, pillow lava and massive mafic flows are overlain by felsic tuffs, wacke, and carbonaceous slate. Sheared mafic tuffs, extensively altered to calcite and chrome-mica, are interbedded with wacke and slate in the upper part of the pile. Serpentinized ultramafic rocks occupy shear zones within the mafic tuffs. Zircons from a massive felsite, which apparently represents a dome intruded into the base of the volcanic pile, yielded a Tremadocian age of 493 ±2 Ma (McLeod *et al.* 1991).

STRUCTURE AND METAMORPHISM

Structural studies and regional mapping indicate that the principal elements of the tectonometamorphic history of the Gander and Dunnage zones of New Brunswick are remarkably similar, despite their complex, polyphase character (Fyffe 1982b; van der Pluijm and van Staal 1988). The Middle Ordovician and older rocks record evidence of several generations of folds and cleavages (*e.g.*, Helmstaedt 1971, 1973a, b; Irrinki 1979; Venugopal 1979; Stringer and Burke 1985; van Staal and Williams 1984; van Staal 1987) and a complex ductile-brittle faulting history (van Staal and Williams 1988). The deformation is markedly hetero-

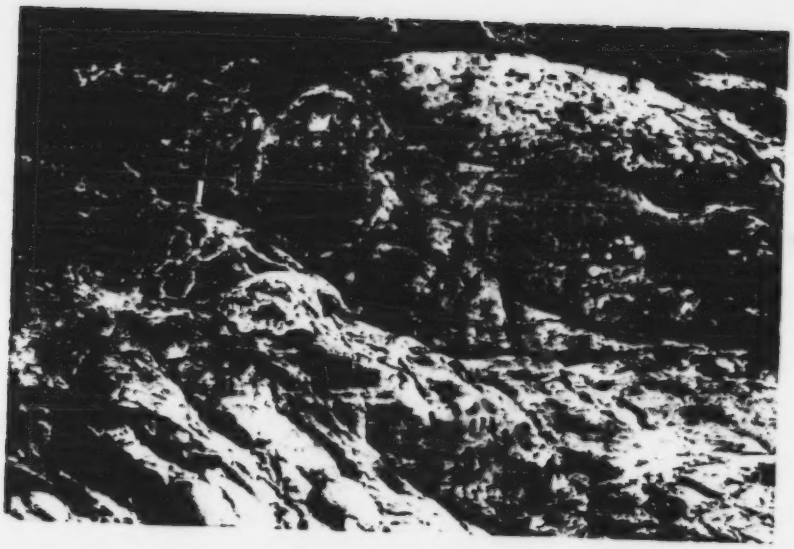


FIGURE 25. Pillow basalt in Calais Formation of the Cookson Group, St. Croix Subzone.

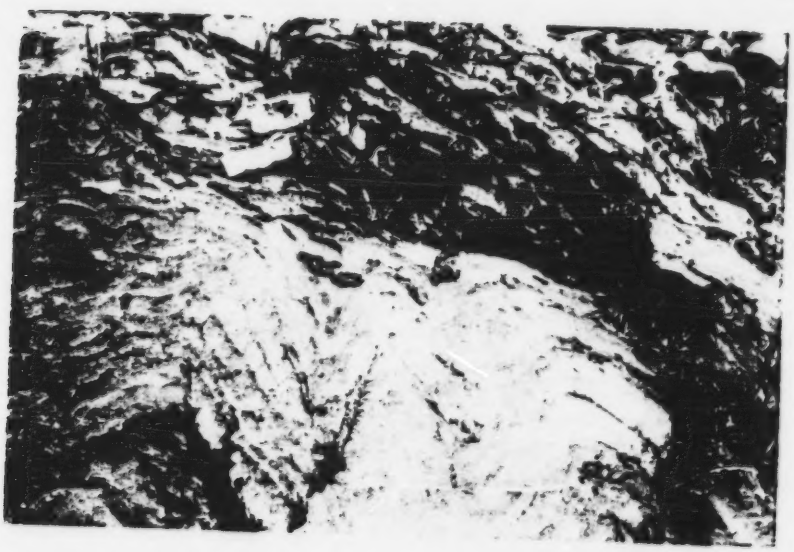


FIGURE 26. Isoclinal F_1 refolded by upright F_2 in interbedded wacke and slate of the Woodland Formation, Cookson Group, St. Croix Subzone.

FIGURE 27. Downward-facing, southward-verging F_3 folds in interbedded wacke and slate of the Digdeguash Formation, Cookson Group, St. Croix Subzone.

geneous on all scales (van Staal 1985, 1986) and, as a result, the amount of strain recorded in the rocks as well as the spectrum of structures present varies from place to place. There is no correspondence between structural styles and stratigraphic divisions. A notion that older rocks exhibit greater strain and number of fold generations have led to tenuous tectonic interpretations. For instance, McBride (1976a, b), Pajari *et al.* (1977), and Rast and Stringer (1980) claimed the existence of a cryptic, angular unconformity within the Tetagouche Group on the basis of a lesser degree of deformation in the late Caradocian (*D. clingani* zone) black phyllites at the very top of the Tetagouche Group. This unconformity was cited as evidence for the existence of the classical Middle Ordovician Taconic Orogeny. Subsequent work (van Staal *et al.* 1988a) failed to substantiate this observation and instead demonstrated that the earliest penetrative structures affecting the Miramichi and Tetagouche groups are also present in the late Caradocian black phyllites.

The polyphase nature of the deformation has been studied most intensively in the northern part of New Brunswick, mainly because of relatively good outcrop, the presence of three dimensional exposure in mines and open pits (*e.g.*, van Staal and Williams 1984, 1986) and its immediate application to ongoing exploration. At least five generations of structures (D_1-D_5) have been recognized on basis of overprinting relationships. They form part of one continuous orogenic event that is constrained between the Late Ordovician and the Middle Devonian on basis of paleontological data, $^{40}Ar/^{39}Ar$ age dates (van Staal *et al.* 1990; Ravenhurst and van Staal, unpublished data) and U-Pb zircon ages (see below). The earliest structures (D_1) are interpreted to have formed by a progressive, thrusting in an accretionary wedge setting (Figure 18, Stage D; van Staal 1987; van Staal *et al.* 1990). These structures comprise recumbent to steeply inclined, intrafolial, non-cylindrical folds (*e.g.*, sheath folds) and a bedding-parallel, transposition foliation. Narrow zones of high strain mark the sites of ductile thrusts (van Staal and Williams 1984; van Staal 1987). The geometry of the thrust "cut-offs" and volcanic horses (Figure 7) suggests that the thrusting was in a southerly or easterly direction. Such a sense of movement is consistent with the generally steeply plunging L_1 stretching lineation and a few kinematic indicators.

The D_1 deformation is commonly accompanied by pumpellyite-actinolite- and/or high-pressure greenschist-facies metamorphism (M_1) in the Armstrong Brook Subzone (van Staal *et al.* 1990). A relatively narrow but extensive zone of M_1 blueschist-facies metamorphism (Skinner 1974; Trzcienski *et al.* 1984) marks the tectonic contact between the Armstrong Brook and Bathurst subzones (van Staal *et al.* 1990). A few S_1 muscovites analysed in the Bathurst Subzone are phengites as opposed to the more

FIGURE 28. Tight F_1 folds in thin-bedded quartz arenite and slate of the Kendall Mountain Formation, Cookson Group, St. Croix Subzone.

ideal muscovites found in the S_2 foliation (van Staal 1985). These variations in muscovite composition may reflect decompression between D_1 and D_2, and suggest that D_1 was associated with a relatively high-pressure regional metamorphism (M_1), although blueschist-facies conditions were not reached in the Bathurst Subzone. M_1 metamorphic conditions in the Bathurst Subzone varied from the prehnite-pumpellyite facies to the greenschist facies. The increase in metamorphic grade (*e.g.*, biotite isograd) toward the southwest (Helmstaedt 1973a; Skinner 1974) appears to be mainly an M_2 effect, superimposed on M_1 (see below). The D_1 deformation and associated metamorphism (M_1) started in the Late Ordovician and probably lasted into the Early Silurian (van Staal *et al.* 1990; see below). Exhumation of parts of the accretionary wedge started at least in the Early Silurian (see also van Staal *et al.* 1990), since the Fournier Group is locally unconformably overlain by Llandoverian conglomerates and red beds in the Belledune Subzone (Noble 1976; Nowlan 1988b) and by Ludlovian conglomerates, containing metagabbro pebbles (Figure 29) of the Middle Ordovician Upsalquitch gabbro (Helmstaedt 1971) in the Armstrong Brook Subzone.

The D_2 deformation was penetrative and resulted in close to isoclinal, upright folds (F_2), which generally refolded all the earlier D_1 structures into steeply dipping attitudes (steep belts). The upright F_2 folds are refolded by open to tight, recumbent F_3 folds (in part referred to as F_5 by van Staal and Williams 1984). Where the D_3 strain is high, the D_2 steep belts are deformed into flat belts (van Staal 1987; de Roo *et al.* 1990; de Roo and van Staal 1991). A well-developed flat-lying S_3 transposition foliation is developed in the flat belts (Figure 30), which are subsequently refolded into dome and basin structures by F_4 and F_5 folds (de Roo and van Staal 1991). D_4 structures range from small-scale, open to tight crenulations to large, kilometre-scale folds (F_4), which become tighter toward the Rocky Brook-Millstream Fault. The D_5 structures comprise conjugate and single kink bands and small-scale, open-to-tight chevron and box folds. The Tetagouche Antiform and Nine Mile Brook Synform (Skinner 1974; van Staal 1986, 1987) are major late D_5 structures with wavelengths and amplitudes in the order of several kilometres.

The deformation history of the Silurian rocks in the narrow belt that separates the Armstrong Brook Subzone from the Belledune Subzone (Figure 1) is also polyphase and comprises at least four generations of structures (D_1-D_4). The D_1 structures have only been observed in the Llandoverian rocks of the Limestone Point Formation (Stringer 1975; Noble 1976). They comprise asymmetrical, isoclinal folds that are not accompanied by an axial planar cleavage. The F_1 folds are refolded by upright, cm-km-scale F_2 folds that locally have a weakly developed axial planar cleavage (S_2). The D_2 structures are consistently transected by a strong domainal cleavage (S_3) in an anticlockwise fashion. This cleavage, which is the main tectonic fabric in the Silurian rocks (Stringer 1975), is associated in a few places with asymmetrical, Z-shaped folds (F_3) that overprint the D_2 structures. Toward the major splays of the Rocky Brook-Millstream Fault system, the cleavage is rotated into parallelism with the trend of the F_2 axial planes, suggesting that D_3 is a result of dextral transpression, with the strain partitioned into dextral shear in the narrow fault zones of the Rocky Brook-Millstream system and a more or less coaxial shortening between the fault zones. Shallowly plunging stretching lineations in rocks close to the major splays of the Rocky Brook-Millstream Fault system (*e.g.*, elongated pebbles and porphyroclasts), asymmetrical boudinage and tensional gashes in various stages of

FIGURE 29. Foliated gabbroic boulder within Upper Silurian conglomerate of the Chaleurs Group.

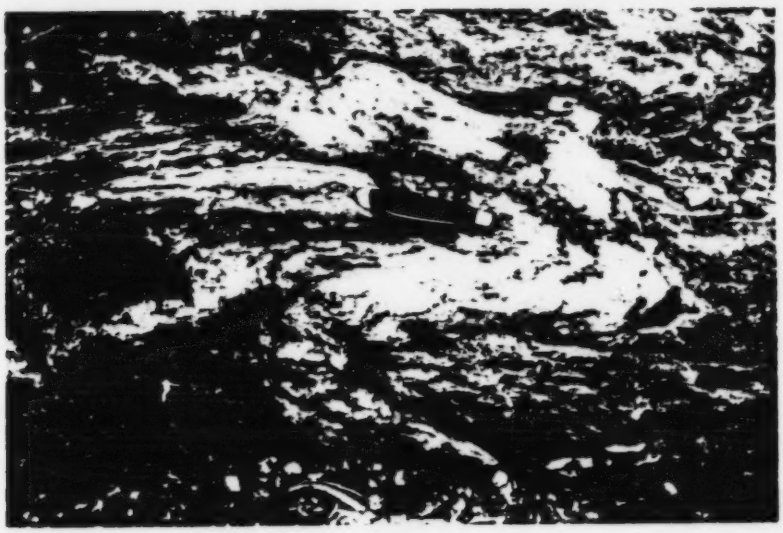


FIGURE 30. Recumbent F_2 folds transposed into shallow-dipping orientation by F_3 within Nepisiguit Falls Formation at Devils Elbow, Bathurst Subzone.

rotation further indicate that the Rocky Brook-Millstream Fault system accommodated a significant amount of dextral transcurrent shear. The D_3 structures are locally overprinted by kink bands and brittle shears (D_4), which may represent the late brittle expression of a continuous progressive, transpression-related deformation. Another major ductile-brittle, dextral fault zone like the Rocky Brook-Millstream Fault is the Catamaran Fault in central New Brunswick (Anderson 1972). Together these two fault zones divide the Miramichi Highlands into rough rhombohedra (van Staal and Williams 1988). D_3-D_4 structures in the Silurian rocks are correlated with the large northeast-trending D_5 structures in the Ordovician rocks south of the Rocky Brook-Millstream Fault. D_4 deformation in the Ordovician rocks may also be related to transpression. The D_3 structures affect Pridolian turbidites of the LaPlante member of the Petit Rocher Formation (Noble 1985; Nowlan 1988c) and appear to be cut by the Early/Middle Devonian Nicholas Denys stock (Davies *et al.* 1969; U-Pb zircon age of 381 ±4 Ma; M.L. Bevier, personal communication, 1991). Porphyries associated with this pluton cut some of the subsidiary faults of the Rocky Brook-Millstream Fault system. A significant part of the dextral, ductile transpression thus took place in the Early Devonian. D_2 and D_3 in the Ordovician rocks, therefore, took place before the Early Devonian. Dextral motion may have continued after the Middle Devonian as a rhombohedral-shaped body of Carboniferous coarse clastic rocks is closely associated with a right-hand step in the main break of the Rocky Brook-Millstream Fault northwest of Bathurst (Figure 1), possibly indicating a small pull-apart basin. D_1 and D_2 structures in the Silurian rocks are best correlated on basis of style and orientation with D_1 and D_2 structures in the Ordovician rocks, respectively. If correct, the D_1 in the Llandoverian rocks should represent structures that formed in the upper levels of the accretionary wedge.

$^{40}Ar/^{39}Ar$ dating of low greenschist-facies, muscovite porphyroblasts related to peak metamorphism (M_2) in the Bathurst Subzone yield cooling ages between 410 and 400 Ma (Ravenhurst and van Staal, unpublished results). These cooling ages suggest that M_2 only slightly predates the earliest known evidence for dextral transpression associated with the Rocky Brook-Millstream Fault, using the absolute time scale of Palmer (1983). The M_2 metamorphism is marked by: (1) the introduction of biotite at the expense of chlorite and K-feldspar in the felsic volcanic and epiclastic rocks; (2) hornblende at the expense of actinolite in mafic rocks; and (3) grunerite, garnet, and rare chloritoid in the iron formation or Fe/Mn-rich metalliferous sediments (van Staal 1985). These porphyroblasts grew across the S_1 cleavage and are locally deformed by F_2. Peak M_2 metamorphic conditions were thus reached after the main D_1 deformation but before the end of D_2 deformation. Recrystallization of biotite and clino-amphiboles accompanied F_4 but not F_5 folding. Widespread alteration of the porphyroblasts to chlorite, Fe-hydroxides and epidote took place before F_5 since these alteration products were deformed during this folding event, indicating that metamorphism was certainly retrograde and waning after D_4 deformation.

The cooling ages of the muscovite porphyroblasts and other age constraints suggest that M_2 metamorphism is closely linked in time to the dominantly Late Silurian granitic and associated gabbroic plutons of the bimodal Acadian magmatic suite (Bevier and Whalen 1990) that intrude the Miramichi Highlands and Chaleur Uplands. This suggests a genetical relationship between plutonism and metamorphism. The relationship is further supported by the relative age of porphyroblast growth in the contact aureole of the Late Silurian Mount Elizabeth biotite granite (U-Pb monazite age of 418 ±1 Ma., Bevier 1988). Porphyroblasts of cordierite overgrew relatively open F_2 crenulations but are wrapped-around by the S_2 crenulation cleavage. These microstructures indicate that D_2 and M_2 metamorphism were synchronous with the intrusion of the bulk of the Acadian magmatic suite in the Late Silurian. A similar age relationship was inferred for porphyroblast growth in the contact aureole of the younger, Early Devonian Pabineau granite (van Staal 1987; U-Pb zircon age of 394 ±1 Ma., Bevier 1988). However, this age may not be relevant since the Pabineau granite appears to have intruded its own contact aureole. This relation is indicated by a very thin aureole or absence of an aureole along the southern contact of the granite. The U-Pb zircon age of Bevier (1988) may therefore represent a late intrusive phase that postdates the formation of the contact aureole.

Greenschist- and subgreenschist-facies mineral assemblages are also present in the Hayesville Subzone (Irrinki 1979; Venugopal 1979), but here the grade increases westward into cordierite- and sillimanite-bearing pelites and migmatites and hornblende- and plagioclase-bearing amphibolites (St. Peter 1981; Fyffe 1982a; Fyffe *et al.* 1988a). The earliest growth of sillimanite preceded or accompanied tight folding (F_2) but continued during later open folding (F_3?). This high-temperature–low-pressure type of metamorphism probably correlates with M_2 metamorphism in the

Bathurst Subzone. K-Ar age determinations on micas from these high-grade rocks yield Devonian cooling ages (Wanless *et al.* 1972, 1973). Although some Lower Devonian plutons postdate, at least in part, the M_2 metamorphism, there appears to be an overall spatial and temporal relationship between the abundance of Late Silurian plutonism and high-grade metamorphism throughout central New Brunswick. However, there is no straightforward correlation between individual plutons exposed on surface and metamorphism. Lux *et al.* (1986) explained the high-temperature–low-pressure metamorphism in the adjacent New England States as a result of regional scale contact effects produced by large granitoid plutons. These supposedly spread into sill-like bodies at intermediate crustal levels and were generated by melting of the lower continental crust during thermal relaxation following the Acadian collision. However, this model fails to explain the significant volume of mantle-derived layered mafic-ultramafic intrusions, gabbroic rocks and the large volume of coeval basalts (*e.g.*, McCutcheon and Bevier 1990) that form part of the Acadian magmatic suite (Fyffe *et al.* 1981).

TECTONIC INTERPRETATIONS

Plate tectonic models were first developed for the Appalachians by Bird and Dewey (1970). They proposed that the volcanic rocks of the Tetagouche Group represented the remnants of an island arc, developed above a northwest-dipping subduction zone, which implies that an ocean basin was present between the Avalon Zone of southern New Brunswick and the Miramichi Highlands. However, this is not consistent with the Celtic and North Atlantic faunas present in the lower parts of the Tetagouche Group (Nowlan 1981; Neuman 1984). Rast and Stringer (1974) and Rast *et al.* (1976) emphasized the lithological similarities of the Cookson and Miramichi groups, a correlation which was subsequently strengthened by Fyffe *et al.* (1983) and justifies their being combined into the Gander Zone (see above). Furthermore, the Lower Ordovician black phyllites, which generally occur at the bottom of the Cookson and top of the Miramichi groups, may onlap onto the Avalon Zone (Rast and Stringer 1974; Ludman 1987), which, if correct, would suggest that the Gander and Avalon zones were juxtaposed or in close proximity by Lower Ordovician times. Such an interpretation is consistent with the high southern paleolatitudes obtained for the Tetagouche Group from paleomagnetic studies (van der Pluijm and van der Voo 1991) and the Lower Ordovician Celtic faunas (Neuman 1984). This lends itself to the possibility that the Avalon Zone or Avalon Composite Terrane (Keppie 1989) forms the continental basement for most of the Gander Zone (Dunning and O'Brien 1989). Pb and Nd isotopic studies of granitoids in the Gander (Bevier 1987) and Avalon zones (Whalen *et al.* 1989) are inconclusive, although they exclude juvenile Avalonian crust typical of the eastern part of the Avalon Zone as a potential basement. This interpretation is supported by Pan-African or Trans-Amazonian detrital zircons in the Miramichi Group (David *et al.* 1991), which suggest a paleogeographic position close to that of the Avalon composite terrane. Combined, these data argue against the existence of an ocean basin between the Miramichi Highlands and the Avalon Zone.

An alternative model to that of Bird and Dewey (1970) was proposed by Pajari *et al.* (1977) and Rast and Stringer (1980) who suggested that the Tetagouche Group was an Andean-type magmatic arc built on Gander Zone rocks, *i.e.*, Miramichi group, above a southeastward-dipping subduction zone. In this model, the Miramichi Group represents the slope/rise portion of a passive margin developed on the southeastern side of Iapetus (Ruitenberg *et al.* 1977; Williams 1979). Such an interpretation is compatible with the sparsely preserved sedimentary structures, and overall turbiditic character of the Miramichi Group. Results of recent petrochemical studies have shown that only the volcanic rocks of the Lower Ordovician Oak Mountain Formation and correlatives in the Miramichi Highlands of Maine have arc-like compositions (Dostal 1989; Winchester and van Staal unpublished data). The Lower Ordovician andesites and felsites in the Annidale belt in the St. Croix Subzone may also belong to this arc, although the age relationships between the various volcanic suites are poorly understood. The associated serpentinites may be correlatives of the Lower Ordovician ophiolitic rocks that occur in the Exploits Subzone of Newfoundland and may have been emplaced on the Gander Zone rocks during the Penobscotian-Ganderian orogeny (Williams and Piasecki 1990; van Staal and Williams 1991). The Middle Ordovician volcanic rocks of the Tetagouche Group in the central and northern Miramichi Highlands on the other hand have compositions typical of a rifting suite (van Staal *et al.* 1991), whereas coeval or younger oceanic crust (Sullivan *et al.* 1990) preserved in the Armstrong Brook and Belledune subzones formed in a suprasubduction zone setting. Middle Ordovician arc rocks occur in the Popelogan Subzone. The Middle Ordovician rocks of the Dunnage Zone in New Brunswick are therefore interpreted as the remnants of a west-facing magmatic arc (Popelogan

arc) with a short-lived (≈ 15 Ma, Figure 8) back-arc basin (Figure 18; Stage C). This back-arc basin possibly developed into a small ocean basin, *i.e.*, Iapetus II, van der Pluijm and van Staal (1988). Equivalents of the Popelogan arc in Newfoundland are probably represented by the Middle Ordovician arc volcanics in the Victoria Lake and Wild Bight groups (Dunning *et al.* 1991; Swinden *et al.* 1990) of the Exploits Subzone.

Closure of the back-arc basin by means of northwestward-directed subduction (Figure 18; Stage D) was probably initiated in the late Caradocian or early Ashgillian, following a polarity reversal induced by the collision of the Popelogan arc with the Humber Zone or Laurentian continental margin (van Staal *et al.* 1990, 1991). Independent evidence for a Caradocian collision between the Popelogan arc and Humber Zone is scarce, but may be represented by a Caradocian hiatus between the Ashgillian Grog Brook turbidites and the underlying Popelogan Formation (see section on the Popelogan Subzone). A similar hiatus is present between the Middle Ordovician Arsenault Formation and the Garin Formation, a correlative of the Grog Brook Group in the southern Gaspé Peninsula of Quebec, and in northern Maine (Riva and Malo 1988), suggesting that it has regional significance. Resubmergence of this part of the Dunnage Zone in the Late Ordovician is equated with the onset of turbidite deposition in a successor basin situated in the fore-arc area above the newly established northwest-dipping subduction zone. The accretion of the Popelogan arc is probably unrelated to a slightly earlier collision between the Taconic arc (such as the Notre Dame Subzone of Newfoundland) and Laurentia (Taconic orogeny *sensu stricto*) according to recent paleomagnetic data (van der Pluijm and van der Voo 1991).

The timing of the collision between the eastern margin of the back-arc basin and Laurentia, which by this stage included the Taconian and Popelogan arcs, is not well constrained. This is mainly because the original relationships between the Lower Silurian and Ordovician rocks are generally obscured by faulting. This also applies to the eastern boundary of the Miramichi Highlands with the Fredericton Belt (Figure 1), where the remnants of a foredeep are potentially preserved (van Staal *et al.* 1990). The following lines of evidence, however, suggest that collision and amalgamation of the Avalon, Gander, and Dunnage zones took place before the Late Silurian, probably close to the Ordovician/Silurian boundary: (1) the Acadian magmatic suite of bimodal plutonic and extrusive rocks cross all boundaries between the Dunnage, Gander and Avalon zones, including a late Ordovician/Early Silurian blueschist suture (van Staal *et al.* 1990) that links the Dunnage and Gander zones by at least the Late Silurian; (2) the regional M_2 high-temperature–low-pressure metamorphism is Late Silurian in age, which should represent a minimum age for collision; and Late Ordovician/Early Silurian $^{40}Ar/^{39}Ar$ ages of phengite and crossite, developed in Tetagouche Group basalts caught up in the blueschist suture zone (van Staal *et al.* 1990), suggest that parts of the eastern margin or transitional crust entered the subduction zone during the Ashgillian; and (3) the oldest known rocks in the Fredericton Belt that link the Miramichi and St. Croix subzones and their correlatives in Maine (Vassalboro or Sangerville Formation) are early Llandoverian (*M. cyphus* zone, see Fyffe this volume) sandstones and shales of the Kingsclear Group. The Fredericton Belt is bounded on both sides by rocks of the Gander Zone and its Silurian rocks contain detritus eroded form the nearby Tetagouche Group rocks (Fyffe and Riva 1990) and Nd-isotope studies on granites (Whalen *et al.* 1989) suggest that the crustal basement to the Fredericton Belt is similar to that of the St. Croix and Miramichi subzones. This early Llandoverian age sets a minimum age for the start of collision (post-Taconian orogeny), irrespective of whether these turbidites represent foredeep deposits or an unconformable, post-collisional cover sequence.

Deformation continued after the collision started (see above). The multiply deformed Lower Silurian rocks of the Chaleurs Group in northern New Brunswick are in turn unconformably overlain by Upper Silurian (Pridolian) or lowest Devonian sandstones and conglomerates (*e.g.*, New Mills Formation; Fyffe and Noble 1985), which appear to have undergone a less complex deformation. These conglomerates contain large boulders of the underlying Lower Silurian rocks, some foliated (McCutcheon and Bevier 1990), indicating rapid exhumation and tectonic activity before the Late Silurian. In western New Brunswick, however, the Silurian sequence appears to be continuous into the Lower Devonian. The central part of the northern Appalachians thus seems to record an intimate interplay between deformation, sedimentation and magmatic activity (see also Dunning *et al.* 1990), including mantle derived melts. We suggest that this Silurian orogenic phase records continuous collision in the Early Silurian (probably having an oblique component) followed by delamination of the lithospheric mantle (Bird 1978), causing upwelling and partial melting of the asthenosphere (Figure 18; Stage E). Delamination of the lithospheric mantle should result in rapid uplift, possibly followed by gravitational collapse of the collision zone (England and

Houseman 1988). Gravitational collapse provides a mechanism for the formation of the flat belts during D_3. Subsequent cooling of the lithosphere would cause subsidence that could explain the formation of the Late Silurian/Devonian successor basins. D_4 and D_5, associated with orogen wide transcurrent movements and transpression, probably record continuous oblique convergence into the Early Devonian.

SUMMARY OF GANDER-DUNNAGE RELATIONSHIPS

Regional analyses show that the Ordovician rocks in the Hayesville, Bathurst, and Armstrong Brook subzones of the Miramichi Highlands, along with the Belledune, Elmtree, and Popelogan subzones of the Chaleur Uplands have similar stratigraphy. Volcanism started in middle/late Arenigian, peaked in the Llanvirnian and was finished by the earliest Caradocian. Coeval magmatism formed oceanic lithosphere in the Belledune and Armstrong Brook subzones, coeval with deposition of metalliferous sedimentary rocks. Deposition of red and black shales, volcaniclastic sediments and limestone was in part coeval with volcanic activity mainly in Llandeilian to early Caradocian times. The area was covered by an extensive, but diachronous blanket of black shale and chert, in Llandeilian-Caradocian time (*N. gracilis-D. clingani* zones), a period during which most of the central part of the New Brunswick Appalachians was starved of coarse clastic sediments. A similar graptolite fauna is present in the Point Leamington greywacke of the Exploits Group in Newfoundland (Riva and Malo 1988). This black shale represents an excellent marker horizon, analogous to the black shale unit in the Dunnage Zone of Newfoundland (*e.g.*, Dean 1978; van der Pluijm *et al.* 1987). Early to Middle Ordovician rocks in the Bathurst and Hayesville subzones are similar to rocks of the Exploits and Indian Bay subzones in Newfoundland (Neuman 1984; O'Neill and Knight 1988), and all contain the same faunas. The correlation with the Exploits Subzone is further strengthened by a U-Pb zircon age of 468 ± 2 Ma for a felsic volcanic of the Bay du Nord Group (Dunning *et al.* 1990) and similarities between lead isotopes from massive sulphides of the Tetagouche Group with those of the Bay du Nord and Baie d'Espoir groups (Swinden and Thorpe 1984). This indicates that recognizable rock packages representing similar settings can be traced along considerable lengths of the orogen as earlier emphasized by Williams (1979). Tectonic models should therefore be consistent with all critical data preserved in various parts of the orogen.

In contrast to the mainly tectonic Dunnage-Gander contacts in Newfoundland, the weight of geological evidence in New Brunswick favours the interpretation that most of the Tetagouche Group of the Dunnage zone represents a conformable to disconformable stratigraphic cover to the Miramichi Group of the Gander Zone. Although contacts are commonly tectonized, field relationships do not support the idea that the numerous bodies of Middle Ordovician volcanic and sedimentary rocks represent the remnants of a once enormous klippe of Dunnage Zone rocks above Gander Zone rocks.

Most geologists who have worked in New Brunswick consider the rocks formerly referred to as the upper and lower Tetagouche Group as a single tectonostratigraphic unit. This practice is discontinued since the Tetagouche Group of the Miramichi Highlands includes unrelated rocks. We restrict the name Tetagouche Group to the Middle Ordovician volcanic and associated sedimentary rocks and consider these to be part of the Dunnage Zone. Underlying clastic rocks, which can be correlated with the Gander Group of Newfoundland, are named the Miramichi Group and are included in the Miramichi Subzone of the Gander Zone. Rocks of the Elmtree Subzone are very similar to those found in the Bathurst Subzone, but differ from those found in the Armstrong Brook and Belledune subzones. The tectonic boundary between the Pointe-Verte and Elmtree formations is, therefore, interpreted as a continuation of the Armstrong Brook-Bathurst subzone boundary, which has been dextrally offset along the Rocky Brook-Millstream Fault. This tectonic boundary is interpreted as the suture of "Iapetus II" (van Staal *et al.* 1990). Further support is given by Nd and Pb isotopic ratios of granites on opposite sides of the suture, which indicate differences in source areas (Bevier 1987; Whalen *et al.* 1989, personal communication, 1990).

The Middle Ordovician rocks of the New Brunswick Dunnage Zone were deposited on an ophiolitic substrate and on continental crust of the Gander Zone. A similar situation may exist in Newfoundland (van Staal and Williams 1991).

REFERENCES

ALCOCK, F.J. 1941. Jacquet River and Tetagouche River map-areas; Geological Survey of Canada, Memoir 227, 46 p.

ANDERSON, F.D. 1972. The Catamaran Fault, north-central New Brunswick. Canadian Journal of Earth Sciences, 9: 1278-1286.

BARNES, C.R., NORFORD, B.S., and

SKEVINGTON, D. 1981. The Ordovician system in Canada. International Union of Geological Sciences, Publication No. 8, 27 p.

BEVIER, M.L. 1987. Pb isotopic ratios of Paleozoic granitoids from the Miramichi terrane, New Brunswick, and implications for the nature and age of the basement rocks. *In* Radiogenic Age and Isotopic Studies: Report 1. Geological Survey of Canada, Paper 87-2, pp. 43-50.

--------- 1988. U-Pb geochronologic studies of igneous rocks in New Brunswick. *In* Thirteenth Annual Review of Activities, Project Resumes, *Edited by* S.A. Abbott. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Information Circular 88-2, pp. 134-140.

--------- 1990. Preliminary U-Pb geochronologic results for igneous and metamorphic rocks, New Brunswick. *In* Project summaries for 1989, Fourteenth Annual Review of Activities. *Edited by* S.A. Abbott. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Information Circular 89-2 (Second Edition), pp. 208-212.

BEVIER, M.L., and WHALEN, J.B. 1990. Tectonic significance of Silurian magmatism in the Canadian Appalachians. Geology, **18**: 411-414.

BIRD, P. 1978. Initiation of intracontinental subduction in the Himalaya. Journal of Geophysical Research, **83**: 4975-4987.

BIRD, J.M., and DEWEY, J.F. 1970. Lithosphere plate-continental margin tectonics and the evolution of the Appalachian Orogen. Geological Society of America Bulletin, **81**: 1031-1060.

BOLTON, T. 1968. Report on GSC locality 82201. Geological Survey of Canada, Paleontology Section.

BOONE, G.M., and BOUDETTE, E.L. 1989. Accretion of the Boundary Mountains terrane within the northern Appalachian orthotectonic zone. Geological Society of America, Special Paper 228, pp. 17-42.

CROUSE, G.W. 1981. Geology of parts of Burnthill, Clearwater and McKiel brooks, map-areas K-14, K-15, K-16 (Parts of 21 J/15 and 21 J/10). New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 81-5, 46 p.

CUMMING, L.M. 1967. Geology of the Passamaquoddy Bay region, Charlotte County, New Brunswick. Geological Survey of Canada, Paper 65-29, 36 p.

DAVID, J., and GARIEPY, C. 1990. Early Silurian orogenic andesites from the central Quebec Appalachians. Canadian Journal of Earth Sciences, **27**: 632-643.

DAVID, J., GARIEPY, C., and MACHADO, N. 1991. U-Pb geochronology of detrital zircons from the Tetagouche Group, New Brunswick. *In* Geological Association of Canada/ Mineralogical Association of Canada, Joint Annual Meeting with Society of Economic Geologists, Toronto, Program with Abstracts, **16**: A28.

DAVIES, J.L. 1966. Geology of Bathurst-Newcastle area, N.B. *In* Guidebook, Geology of Parts of Atlantic Provinces. *Edited by* W.H. Poole. Annual Meetings, Geological Association of Canada and Mineralogical Association of Canada, Halifax, pp. 33-43.

--------- 1972a. The geology and geochemistry of the Austin Brook area, Gloucester County, New Brunswick, with special emphasis on the Austin Brook iron formation. Unpublished Ph.D. thesis, Carleton University, Ottawa, Ontario, 254 p.

--------- 1972b. The Bathurst-Newcastle area. International Geological Congress, XXIV, Field Guide A-58, pp. 50-58.

--------- 1979. Geological map of northern New Brunswick. New Brunswick Department of Natural Resources, Mineral Resources Branch, Map NR-3.

DAVIES, J.L., FYFFE, L.R., and McALLISTER, A.L. 1983. Geology and massive sulphides of the Bathurst area, New Brunswick. *In* Field Trip Guidebook to Stratabound Sulphide Deposits, Bathurst Area, New Brunswick, Canada and West-Central New England, U.S.A. *Edited by* D.E. Sangster. International Geological Correlation Program-Correlation of Caledonian Stratabound Sulphides, Symposium, Ottawa, Ontario, Canada, Miscellaneous Report 36, pp. 1-30.

DAVIES, J.L., TUPPER, W.M., BACHINSKI, D., BOYLE, R.W., and MARTIN, R. 1969. Geology and mineral deposits of the Nigadoo River-Millstream River area, Gloucester County, New Brunswick. Geological Survey of Canada, Paper 67-49, 70 p.

DEAN, P.L. 1978. The volcanic stratigraphy and metallogeny of Notre Dame Bay, Newfoundland. Memorial University of Newfoundland, Geology Report, 7, 204 p.

DEAN, W.T. 1975. Report on GSC locality 91889. Geological Survey of Canada, Eastern Paleontology Section.

DE ROO, J.A., and VAN STAAL, C.R. 1991. The structure of the Half Mile Lake Region, Bathurst Camp, New Brunswick. *In* Current Research. Geological Survey of Canada, Ottawa, Paper 91-1D.

DE ROO, J.A., MORETON, C., WILLIAMS, P.F., and VAN STAAL, C.R. 1990. The structure of the Heath Steele Mines region, Bathurst Camp, New Brunswick. Atlantic Geology, **26**: 27-41.

DOSTAL, J. 1989. Geochemistry of Ordovician volcanic rocks of the Tetagouche Group of southwestern New Brunswick. Atlantic Geology, **25**: 199-209.

DUNNING, G.R., and KROGH, T.E. 1985. Geochronology of ophiolites of the Newfoundland Appalachians. Canadian Journal of Earth Sciences, **22**: 1659-1670.

DUNNING, G.R., and O'BRIEN, S.J. 1989. Late Proterozoic-Early Paleozoic crust in the Hermitage flexure, Newfoundland Appalachians: U/Pb ages and tectonic significance. Geology, **17**: 548-551.

DUNNING, G.R., O'BRIEN, S.J., COLEMAN-SADD, S.P., BLACKWOOD, R.F., DICKSON, W.L., O'NEILL, P.P., and KROUGH, T.E. 1990. Silurian orogeny in the Newfoundland Appalachians. Journal of Geology, **98**: 895-913.

DUNNING, G.R., SWINDEN, H.S., KEAN, B.F., EVANS, D.T.W., and JENNER, G.A. 1991. A Cambrian island arc in Iapetus; geochronology and geochemistry of the Lake Ambrose volcanic belt, Newfoundland Appalachians. Geological Magazine, **128**: 1-17.

ENGLAND, P.C., and HOUSEMAN, G.A. 1988. The mechanics of the Tibetan plateau: Royal Society of London Philosophical Transactions, ser. A, **326**: 301-320.

FLAGLER, P.A., and SPRAY, J.G. 1991. Generation of plagiogranite by amphibolite anatexis in oceanic shear zones. Geology, **19**: 1-96.

FYFFE, L.R. 1976. Correlation of geology in the southwestern and northern parts of the Miramichi Zone. *In* 139th Annual Report, New Brunswick Department of Natural Resources, Province of New Brunswick, pp. 137-141.

--------- 1977. Comparison of some tectono-stratigraphic zones in the Appalachians of Newfoundland and New Brunswick: Discussion. Canadian Journal of Earth Sciences, **14**: 1468-1469.

--------- 1982a. Geology of Woodstock (sheet 21 J). New Brunswick Department of Natural Resources, Map NR-4.

--------- 1982b. Taconian and Acadian structural trends in central and northern New Brunswick. *In* Major Structural Zones and Faults of the Northern Appalachians. *Edited by* P. St-Julien and J. Beland. Geological Association of Canada, Special Paper 24, pp. 117-130.

--------- 1986. A recent graptolite discovery from the Fournier Group of northern New Brunswick. *In* Eleventh Annual Review of Activities, Project Resumés, 1986. *Edited by* S.A. Abbott. New Brunswick Department of Natural Resources and Energy, Mineral Resources Division, Information Circular 86-2, pp. 43-45.

--------- 1988. Bedrock geology of the McAdam-St. Croix River area. *In* Thirteenth Annual Review of Activities, Project Resumes, 1988. *Edited by* S.A. Abbott. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Information Circular 88-2, pp. 70-75.

FYFFE, L.R., and FRICKER, A. 1987. Tectonostratigraphic terrane analysis of New Brunswick. Maritime Sediments and Atlantic Geology, **23**: 113-123.

FYFFE, L.R., and NOBLE, J.P.A. 1985. Stratigraphy and structure of the Ordovician, Silurian and Devonian of northern New Brunswick. *In* Field Guide, Excursion 4, Geological Association of Canada, Mineralogical Association of Canada, Fredericton, N.B., II, pp. 1-56.

FYFFE, L.R., and PICKERILL, R.K. 1986. Comment and Reply on "Timing of terrane accretion in eastern and east-central Maine". Geology, **14**: 1051-1052.

FYFFE, L.R., and PRONK, A.G. 1985. Bedrock and surficial geology - rock and till geochemistry in the Trousers Lake area, Victoria County, New Brunswick. New Brunswick Department of Natural Resources, Mineral Resources Division, Report of Investigation 20, 74 p.

FYFFE, L.R., and RIVA, J. 1990. Revised stratigraphy of the Cookson Group based on new paleontological, sedimentological, and structural evidence. Atlantic Geology, **26**: 271-276.

FYFFE, L.R., IRRINKI, R.R., and CORMIER, R.F. 1977. A radiometric age of deformed granitic rocks in north-central New Brunswick. Canadian Journal of Earth Sciences, **14**: 1687-1689.

FYFFE, L.R., PAJARI, G.E., and CHERRY, M.E. 1981. The Acadian plutonic rocks of New Brunswick. Maritime Sediments and Atlantic Geology, **17**: 23-36.

FYFFE, L.R., FORBES, W.H., and RIVA, J. 1983. Graptolites from the Benton area of west-central New Brunswick and their regional significance. Maritime Sediments and Atlantic Geology, **19**: 117-125.

FYFFE, L.R., BARR, S.M., and BEVIER, M.L. 1988a. Origin and U-Pb geochronology of amphibolite-facies metamorphic rocks, Miramichi Highlands,

New Brunswick. Canadian Journal of Earth Sciences, **25**: 1674-1686.

FYFFE, L.R., STEWART, D.B., and LUDMAN, A. 1988b. Tectonic significance of black pelites and basalts in the St. Croix terrane, coastal Maine and New Brunswick. Maritime Sediments and Atlantic Geology, **24**: 281-288.

FYFFE, L.R., VAN STAAL, C.R., and WINCHESTER, J.A. 1990. Late Precambrian-Early Paleozoic volcanic regimes and associated massive sulphide deposits in the northeastern mainland Appalachians. Canadian Institute of Mining and Metallurgy Bulletin, **83**, No. 938, pp. 70-78.

GUMMER, P.K., VON GUTTENBERG, R., and FERGUSON, L. 1978. A recent fossil discovery in the Tetagouche volcanic complex of New Brunswick. Paper presented at the New Brunswick Annual Meeting of the Canadian Institute of Mining and Metallurgy, Bathurst, N.B.

HALL, B.A. 1970. Stratigraphy of the southern end of the Munsungun Anticlinorium, Maine. Maine Geological Survey, Bulletin 22, 63 p.

HAQ, B.U., and VAN EYSINGA, W.B. 1987. Geological Time Table, 4th Edition. Elsevier, Amsterdam, Holland.

HARLAND, W.B., COX, A.V., LLEWELLYN, P.G., PICKTON, C.A.G., SMITH, A.G., and WALTERS, R. 1982. A geologic time scale. Cambridge University Press, Cambridge, United Kingdom.

HARLEY, D.N. 1979. A mineralized Ordovician resurgent caldera complex in the Bathurst-Newcastle mining district, New Brunswick, Canada. Economic Geology, **74**: 786-796.

HELMSTAEDT, H. 1971. Structural geology of Portage Lakes area, Bathurst-Newcastle District, New Brunswick. Geological Survey of Canada, Paper 70-28, 52 p.

--------- 1973a. Structural geology of the Bathurst-Newcastle district. *In* Geology of New Brunswick, Field Guide to Excursions. *Edited by* N. Rast. New England Inter-collegiate Geological Conference, pp. 34-46.

--------- 1973b. Discussions: deformation-al history of the Caribou strata-bound deposits, Bathurst, New Brunswick, Canada. Economic Geology, **68**: 571-572.

IRRINKI, R.R. 1974. The structural geology and regional metamorphism of the Miramichi Zone (north), New Brunswick. Unpublished M.Sc. thesis, Acadia University, Wolfville, Nova Scotia, 152 p.

--------- 1979. Geology of North and South Little Sevogle Rivers–North Branch, Little Southwest Miramichi River–McKendrick and Catamaran lakes region, map-areas O-12, N-12, and N-13 (Part of 21 J/16). New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 79-1, 36 p.

--------- 1980. Geology of Kennedy Lakes-Little Dungarvon and South Renous rivers region (map areas M-13, M-14, M-15 and Part of M-16). New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 80-2, 39 p.

KENNEDY, M.J. 1975. Repetitive orogeny in the northeastern Appalachians - New plate models based on Newfoundland examples. Tectonophysics, **28**: 39-87.

--------- 1976. Southeastern margin of the northeastern Appalachians: Late Precambrian orogeny on a continental margin. Geological Society of America Bulletin, **87**: 1317-1324.

KENNEDY, D.J., BARNES, C.R., and UYENO, T.T. 1979. A Middle Ordovician conodont faunule from the Tetagouche Group, Camel Back Mountain, New Brunswick. Canadian Journal of Earth Sciences, **16**: 540-551.

KEPPIE, J.D. 1989. Northern Appalachian terranes and their accretionary history. Geological Society of America, Special Paper 230, pp. 159-192.

LANGTON, J.P., and VAN STAAL, C.R. 1989. Geology of the Ordovician Elmtree Terrane. *In* Geological Association of Canada/Mineralogical Association of Canada, Joint Annual Meeting, St. John's, Newfoundland, Program with Abstracts, **14**, p. A11.

LUDMAN, A. 1987. Pre-Silurian stratigraphy and tectonic significance of the St. Croix Belt, southeastern Maine. Canadian Journal of Earth Sciences, **24**: 2459-2469.

LUTES, G. 1979. Geology of Fosterville-North and Eel lakes, map area G-23 and Canterbury-Skiff Lake map area H-23. New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 79-3, 22 p.

LUX, D.R., DE YOREO, J.J., GUIDOTTI, C.V., and DECKER, E.R. 1986. Role of plutonism in low-pressure metamorphic belt formation. Nature, 323, No. 6091, pp. 794-797.

MALO, M. 1988. Stratigraphy of the Aroostook-Perce Anticlinorium in the Gaspe Peninsula, Quebec. Canadian Journal of Earth Sciences, **25**: 893-908.

McALLISTER, A.L. 1960. Massive sulphide deposits in New Brunswick. Canadian Institute of Mining and Metallurgy, Bulletin 53, No. 573, pp. 88-98.

McBRIDE, D.E. 1976a. The structure and stratigraphy of the B-zone, Heath Steele Mines, Newcastle, New Brunswick. Unpublished Ph.D. thesis, University of New Brunswick, Fredericton, New Brunswick, 227 p.

--------- 1976b. Tectonic setting of the Tetagouche Group, host to the New Brunswick polymetallic massive sulphide deposits. *In* Metallogeny and Plate Tectonics. *Edited by* D.F. Strong. Geological Association of Canada, Special Paper 14, pp. 473-485.

McCUTCHEON, S.R., and BEVIER, M.L. 1990. Implications of field relations and U-Pb geochronology for the age of gold mineralization and timing of Acadian deformation in northern New Brunswick. Atlantic Geology, **26**: 237-246.

McLEOD, M.J., JOHNSON, S.C., and RUITENBERG, A.A. 1990. Compilation and correlation of southern New Brunswick. *In* Project Summaries for 1989, Fourteenth Annual Review of Activities. *Edited by* S.A. Abbott. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Information Circular 89-2, pp. 151-159.

McLEOD, M.J., RUITENBERG, A.A., and KROGH, T.E. 1991. A previously unrecognized lower Ordovician sequence in southern New Brunswick: evidence for multistage development of Iapetus? Atlantic Geoscience Society, Program with Abstracts.

McMILLAN, R.H. 1969. A comparison of the geological environments of base metal sulfide deposits of the B Zone and North Boundary Zone at Heath Steele Mines, New Brunswick. Unpublished M.Sc. thesis, University of Western Ontario, London, Ontario, 192 p.

NEUMAN, R.B. 1967. Bedrock geology of the Shin Pond and Stacyville quadrangles, Maine. U.S. Geological Survey, Professional Paper 524-1, 47 p.

--------- 1968. Paleogeographic implications of Ordovician shelly fossils in the Magog Belt of the northern Appalachian region. *In* Studies of Appalachian Geology: Northern and Maritime. *Edited by* E-An Zen, W.S. White, J.B. Hadley and J.B. Thompson, Jr. Interscience Publishers (a division of John Wiley & Sons), pp. 35-48.

--------- 1984. Geology and paleobiology of islands in the Ordovician Iapetus Ocean: review and implications. Geological Society of America, Bulletin, **94**: 1188-1201.

NOBLE, J.P.A. 1976. Silurian stratigraphy and paleogeography, Pointe Verte area, New Brunswick, Canada. Canadian Journal of Earth Sciences, **13**: 537-546.

--------- 1985. Occurrence and significance of Late Silurian reefs in New Brunswick. Canadian Journal of Earth Sciences, **22**: 1518-1529.

NOWLAN, G.S. 1981. Some Ordovician conodont faunules from the Miramichi Anticlinorium, New Brunswick. Geological Survey of Canada, Bulletin 345, 35 p.

--------- 1983. Report on three samples from limestone in pillow basalts from the Pointe Verte Formation (northern New Brunswick). Submitted for Conodont Analysis by L.R. Fyffe and W.H. Poole. Geological Survey of Canada, Ottawa Paleontology Section, Report 002-GSN-1983, 2 p.

--------- 1986. Report on fifteen samples from Ordovician and Silurian strata of northern New Brunswick. Geological Survey of Canada, Paleontology Subdivision, Report 005-GSN-1986.

--------- 1988a. Report on twelve samples from Lower Paleozoic strata of northern New Brunswick. Geological Survey of Canada, Paleontology Subdivision, Report 011-GSN-1988.

--------- 1988b. Report on one sample from the ? Armstrong Brook Formation at Limestone Point. Geological Survey of Canada, Paleontology Subdivision, Report 004-GSN-1988.

--------- 1988c. Report on fifteen samples from Ordovician and Silurian strata of northern New Brunswick. Geological Survey of Canada, Paleontology Subdivision, Report 010-GSN-1988.

OSBERG, P.H., HUSSEY, A.M., and BOONE, G.M. (editors). 1985. Bedrock geological map of Maine. Maine Geological Survey, Department of Conservation.

O'NEILL, P., and KNIGHT, J. 1988. Geology of the east half of the Weir's Pond (2 E/l) map area and its regional significance. *In* Current Research (1988), Newfoundland Department of Mines, Mineral Development Division, Report 88-l, pp. 165-176.

PAJARI, G.E., Jr., RAST, N., and STRINGER, P. 1977. Paleozoic volcanicity along the Bathurst-Dalhousie geotraverse, New Brunswick, and its relations to structure. *In* Volcanic Regimes in Canada. *Edited by* W.R.A. Baragar, L.C. Coleman, and J.M. Hall. Geological Association of Canada, Special Paper 16, pp. 111-124.

PALMER, A.R. 1983. Decade of North American geology, geologic time scale. Geology, **11**: 503-508.

PHILPOTT, G.R. 1987. Precious-metal and geological investigation of the Charlo River area. *In* Twelfth Annual Review of Activities, Project Résumés,

1987. *Edited by* S.A. Abbott. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Information Circular 87-2, pp. 13-16.

--------- 1988. Precious-metal and geological investigation of the Charlo River area, New Brunswick. *In* Thirteenth Annual Review of Activities, Project Résumés, 1988. *Edited by* S.A. Abbott. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Information Circular 88-2, pp. 20-31.

POOLE, W.H. 1963. Geology, Hayesville, New Brunswick. Geological Survey of Canada, Map 6-1963.

POTTER, R.R. 1964. Upsalquitch Forks map-area. Geological Survey of Canada, Summary of Activities, Field 1963, Paper 64-1, pp. 64-65.

--------- 1969. The geology of Burnt Hill area and ore controls of the Burnt Hill tungsten deposit. Unpublished Ph.D. thesis, Carleton University, Ottawa, Ontario, 136 p.

RAST, N., and STRINGER, P. 1974. Recent advances and the interpretation of geological structure of New Brunswick. Geoscience Canada, 1, No. 4, pp. 15-25.

--------- 1980. A geotraverse across a deformed Ordovician ophiolite and its Silurian cover, northern New Brunswick, Canada. Tectonophysics, 69: 221-245.

RAST, N., KENNEDY, M.J., and BLACKWOOD, R.F. 1976. Comparison of some tectonostratigraphic zones in the Appalachians of Newfoundland and New Brunswick. Canadian Journal of Earth Sciences, 13: 868-875.

RIVA, J., and MALO, M. 1988. Age and correlation of the Honorat Group, southern Gaspe Peninsula. Canadian Journal of Earth Sciences, 25: 1618-1628.

ROY, D.C., and MENCHER, E. 1976. Ordovician and Silurian stratigraphy of northeastern Aroostook County, Maine. *In* Contributions to the Stratigraphy of New England. *Edited by* L.R. Page. Geological Society of America, Memoir 148, pp. 25-52.

RUITENBERG, A.A. 1967. Stratigraphy, structure and metallization Piskahegan-Rolling Dam area, northern Appalachians, New Brunswick, Canada. Leidse Geologische Mededelingen 40: 79-120.

RUITENBERG, A.A., and LUDMAN, A. 1978. Stratigraphy and tectonic setting of Early Paleozoic sedimentary rocks of the Wirral-Big Lake area, southwestern New Brunswick and Southeastern Maine. Canadian Journal of Earth Sciences, 15: 22-32.

RUITENBERG, A.A., FYFFE, L.R., McCUTCHEON, S.R., ST. PETER, C.J., IRRINKI, R.R., and VENUGOPAL, D.V. 1977. Evolution of Pre-Carboniferous tectono-stratigraphic zones in the New Brunswick Appalachians. Geoscience Canada, 4, No.4, pp. 171-181.

SAIF, S.I. 1977. Identification, correlation and origin of the Key Anacon-Brunswick mines ore horizon, Bathurst, New Brunswick. Unpublished Ph.D. thesis, University of New Brunswick, Fredericton, New Brunswick, 292 p.

--------- 1980. Petrographic and geochemical investigation of iron formation and other iron-rich rocks in Bathurst district, New Brunswick. *In* Current Research, Part A. Geological Survey of Canada, Paper 8O-1A, pp. 309-317.

ST. PETER, C. 1978. Geology of parts of Restigouche, Victoria and Madawaska counties, northwestern New Brunswick. New Brunswick Department of Natural Resources, Mineral Resources Branch, Report of Investigation 17, 69 p.

--------- 1981. Geology of North Branch Southwest Miramichi River (map-areas J-14, J-15, J-16). New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 80-1, 61 p.

--------- 1982. Geology of Juniper-Knowlesville-Carlisle area, New Brunswick. New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 82-1, 82 p.

SAUNDERS, A.D., and TARNEY, J. 1984. Geochemical characteristics of basaltic volcanism within back-arc basins. *In* Marginal Basin Geology. *Edited by* B.P. Kokelaar and M.F. Howells. Geological Society of London, Special Publication 16, pp. 59-76.

SKINNER, R. 1974. Geology of Tetagouche Lakes, Bathurst and Nepisiguit Falls map areas, New Brunswick. Geological Survey of Canada, Memoir 371, 133 p.

--------- 1975. Geology of Tuadook Lake map area (21 J/15), New Brunswick. Geological Survey of Canada, Paper 74-33, 9 p.

SKINNER, R., and McALARY, J.D. 1952. Preliminary map, Nepisiguit Falls, Gloucester and Northumberland counties, New Brunswick. Geological Survey of Canada, Paper 53-23.

SMITH, C.H., and SKINNER, R. 1958. Geology of the Bathurst-Newcastle mineral district, New Brunswick. Canadian Institute of Mining and Metallurgy, Bulletin 51, No. 551, pp. 150-155.

SNELLING, N.J. 1985. An interim time scale. *In* The Chronology of the Geological Record. *Edited by*

N.J. Snelling. British Geological Survey, Memoir 10, pp. 261-265.

SPRAY, J.G., FLAGLER, P.A., and DUNNING, G.R. 1990. Crystallization and emplacement chronology of the Fournier oceanic fragment, Canadian Appalachians. Nature, **344**: 232-235.

STRINGER, P. 1975. Acadian slaty cleavage noncoplanar with fold axial surfaces in the northern Appalachians. Canadian Journal of Earth Sciences, **12**: 949-961.

STRINGER, P., and BURKE, K.B.S. 1985. Structures in the southwest New Brunswick. Excursion 9. Geological Association of Canada/ Mineralogical Association of Canada, University of New Brunswick, Fredericton, New Brunswick, 34 p.

SULLIVAN, R.W., and VAN STAAL, C.R. 1990. Age of a metarhyolite from the Tetagouche Group, Bathurst, New Brunswick, from U-Pb isochron analyses of zircons enriched in common Pb. *In* Radiogenic Age and Isotopic Studies: Report 3. Geological Survey of Canada, Paper 89-2, pp. 109-117.

SULLIVAN, R.W., VAN STAAL, C.R., and LANGTON, J.P. 1990. U-Pb zircon ages of plagiogranite and gabbro from the ophiolitic Devereaux Formation, Fournier group, northeastern New Brunswick. *In* Radiogenic Age and Isotopic Studies: Report 3. Geological Survey of Canada, Paper 89-2, pp. 119-122.

SWINDEN, H.S., and THORPE, R.I. 1984. Variations in style of volcanism and massive sulfide deposition in Early-Middle Ordovician island arc sequences of the New Brunswick Central Mobile Belt. Economic Geology, **79**: 1596-1619.

SWINDEN, H.S., JENNER, G.A., FRYER, B.J., HERTOGEN, J., and RODDICK, J.C. 1990. Petrogenesis and paleotectonic history of the Wild Bight Group, an Ordovician rifted island arc in central Newfoundland. Contributions to Mineralogy and Petrology, **105**: 219-241.

THOMAS, M.D., TANCZYK, W.I., CIOPPA, M., and O'DOWD, D.V. 1991. Ground magnetic and rock magnetism studies near the Appalachian Dunnage-Gander terrane boundary, northern New Brunswick. *In* Current Research, Part D. Geological Survey of Canada, Paper 91-1D, pp. 169-178.

TRZCIENSKI, W.E., Jr., CARMICHAEL, D.M., and HELMSTAEDT, H. 1984. Zoned sodic amphibole: petrologic indicator of changing pressure and temperature during tectonism in the Bathurst area, New Brunswick, Canada. Contributions to Mineralogy and Petrology, **85**: 311-320.

TUCKER, R.D., KROGH, T.E., ROSS, R.J. Jr., and WILLIAMS, S.H. 1990. Time-scale calibration by high precision U-Pb zircon dating of interstratified volcanic ashes in the Ordovician and Lower Silurian stratotypes of Britain. Earth and Planetary Science Letters, **100**: 51-58.

VAN DER PLUIJM, B.A., and VAN DER VOO, R. 1991. Paleogeography and accretion of terranes in the northern Appalachians: paleomagnetic and tectonostratigraphic evidence. *In* The Geological Society of America, combined Northeastern and Southeastern sections, Abstracts with Program, **23**, Number 1, p. 143.

VAN DER PLUIJM, B.A., and VAN STAAL, C.R. 1988. Characteristics and evolution of the central mobile belt, Canadian Appalachians. Journal of Geology, **96**: 535-547.

VAN DER PLUIJM, B.A., KARLSTROM, K.E., and WILLIAMS, P.F. 1987. Fossil evidence for fault-derived stratigraphic repetition in the northeastern Newfoundland Appalachians. Canadian Journal of Earth Sciences, **24**: 2337-2350.

VAN STAAL, C.R. 1985. Structure and metamorphism of the Brunswick Mines area, Bathurst, New Brunswick, Canada. Unpublished Ph.D. thesis, University of New Brunswick, Fredericton, New Brunswick, 484 p.

--------- 1986. Preliminary results of structural investigations in the Bathurst Camp of northern New Brunswick. *In* Current Research, Part A. Geological Survey of Canada, Paper 86-1A, pp. 193-204.

--------- 1987. Tectonic setting of the Tetagouche Group in northern New Brunswick: implications for plate tectonic models of the northern Appalachians. Canadian Journal of Earth Sciences, **24**: 1329-1351.

VAN STAAL, C.R., and LANGTON, J.P. 1988. Correlation between the Elmtree and Miramichi terranes: evidence for the Caledonian Orogeny in northeastern New Brunswick. *In* Geological Association of Canada/Mineralogical Association of Canada, Joint Annual Meeting, St. John's, Newfoundland, Program with Abstracts, **13**: A129.

--------- 1990. Geology of Ordovician massive sulphide deposits and their host rocks in northern New Brunswick. *In* Mineral deposits of New Brunswick and Nova Scotia (Field Trip 2). *Edited by* D.R. Boyle. Eighth IAGOD Symposium Field Guide Book, Geological Survey of Canada, Open File 2157, pp. 1-21.

VAN STAAL, C.R., and WILLIAMS, P.F. 1984.

Structure, origin and concentration of the Brunswick No. 6 and No. 12 ore bodies. Economic Geology, 79: 1669-1692.

--------- 1986. Structural interpretation of the Brunswick ore bodies. *In* Geology in the Real World - The Kingsley Dunham Volume. *Edited by* R.W. Nesbitt and J. Nichol. The Institute of Mining and Metallurgy, London, United Kingdom, pp. 451-462.

--------- 1988. Collision along an irregular margin: a regional plate tectonic interpretation of the Canadian Appalachians. Canadian Journal of Earth Sciences, 25: 1912-1916.

--------- 1991. Dunnage Zone-Gander Zone relationships in the Canadian Appalachians. *In* The Geological Society of America, combined Northeastern and Southeastern sections. Abstract with Programs, 23: 143.

VAN STAAL, C.R., LANGTON, J.P., and SULLIVAN, R.W. 1988a. A U-Pb zircon age for the ophiolitic Devereaux Formation, Elmtree Terrane, northeastern New Brunswick. *In* Radiogenic Age and Isotopic Studies: Report 2. Geological Survey of Canada, Paper 88-2, pp. 37-40.

VAN STAAL, C.R., WINCHESTER, J.A. and BEDARD, J.H. 1991. Geochemical variations in Middle Ordovician rocks of the northern Miramichi Highlands and their tectonic significance. Canadian Journal of Earth Sciences, 28:

VAN STAAL, C.R., WINCHESTER, J., and CULLEN, R. 1988b. Evidence for D_1-related thrusting and folding in the Bathurst-Millstream River area, New Brunswick. *In* Current Research, Part B. Geological Survey of Canada, Paper 88-1B, pp. 135-148.

VAN STAAL, C.R., RAVENHURST, C.E., WINCHESTER, J.A., RODDICK, J.C., and LANGTON, J.P. 1990. Post-Taconic blueschist suture in the northern Appalachians of northern New Brunswick, Canada. Geology, 18: 1073-1077.

VENUGOPAL, D.V. 1978. Geology of Benton-Kirkland, Upper Eel River Bend, map area G-22 (21 G/13). New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 78-3, 16 p.

--------- 1979. Geology of Debec Junction-Gibson Millstream-Temperance Vale-Meductic region, map-areas G-21, H-21, I-21, and H-22 (Parts of 21 J/3, 21 J/4, 21 G/13, 21 G/14). New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 79-5, 36 p.

--------- 1981. Geology of Hartland-Woodstock-Nortondale region, map areas H-19, H-20, I-20 (Parts of 21 J/03, 21 J/04, 21 J/05, 21 J/06). New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 81-6, 37 p.

WANLESS, R.K., STEVENS, R.D., LACHANCE, G.R., and DELABIO, R.N. 1972. K-Ar age determinations of samples from various areas of New Brunswick. *In* Age Determinations and Geological Studies. K-Ar isotopic ages, Report 10, Geological Survey of Canada, Paper 71-2, pp. 68-77.

--------- 1973. K-Ar age determinations of samples from various areas of New Brunswick. *In* Age Determinations and Geological Studies. K-Ar isotopic ages, Report 11, Geological Survey of Canada, Paper 71-2, pp. 68-77.

WHALEN, J.B. 1987. Geology of a northern portion of the Central Plutonic Belt, New Brunswick. *In* Current Research, Part A. Geological Survey of Canada, Paper 87-1A, pp. 209-217.

WHALEN, J.B., HAGNER, E., and JENNER, G.A. 1989. Nature of Canadian Appalachians basement terranes as inferred from a Nd isotopic transect. Geological Society of America, Annual Meeting, St. Louis Missouri, Program With Abstracts, 21, No. 6, p. A201.

WHITEHEAD, R.E.S., and GOODFELLOW, W.D. 1978. Geochemistry of volcanic rocks from the Tetagouche Group, Bathurst, New Brunswick, Canada. Canadian Journal of Earth Sciences, 15: 207-219.

WILLIAMS, H. 1978. Tectonolithofacies map of the Appalachian Orogen. Memorial University of Newfoundland, St. John's, Newfoundland, Map 1.

--------- 1979. Appalachian Orogen in Canada. Canadian Journal of Earth Sciences, 16, Part 2, pp. 792-807.

WILLIAMS, H., and PIASECKI, M.A.J. 1990. The Cold Spring Melange and a possible model for Dunnage-Gander zone interaction in central Newfoundland. Canadian Journal of Earth Sciences, 27: 1126-1134.

WINCHESTER, J., and VAN STAAL, C.R. 1988. Middle Ordovician volcanicity in northern New Brunswick: geochemistry and probable tectonic setting. *In* Geological Association of Canada/Mineralogical Association of Canada, Joint Annual Meeting, St. John's, Newfoundland, Program with Abstracts, 13: A135.

YOUNG, G.A. 1911. Bathurst district, New Brunswick. Geological Survey of Canada, Memoir 18E, 105 p.